IMPACT OF LONG- AND SHORT-TERM GEODYNAMIC PROCESSES ON HYDROCARBON RESERVOIRS IN THE GRAND BANKS

by

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A thesis submitted to the Department of Geological Sciences & Geological Engineering

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Abstract

The evolution of the passive margin off the coast of Eastern Canada has been characterized by a series of rifting episodes beginning approximately 200 ma which caused widespread extension of the lithosphere and associated structural anomalies, some with the potential to be classified as a result of lithospheric boudinage. Crustal thinning of competent layers is often apparent in seismic sections, and deeper Moho undulations may appear as repeating elongated anomalies in gravity and magnetic surveys. This investigation supplements our knowledge of analogous examples which have been linked to boudinage as a driving mechanism, to determine that similar structures are evident in the context of the Grand Banks. More recently in the last 20 ka, the region has been subject to crustal warping and Glacial Isostatic Adjustment (GIA)-induced visco-elastic deformation. Numerical simulations were run using different rheological parameters and ice load histories to obtain a model which may be representative of the isostatic response for the Grand Banks. The goal was to assess the potential impact on hydrocarbon reservoirs and trapping structures as a consequence of GIA processes, which may include various deformation-related implications. Comparisons may be drawn to related studies, including the postglacial implications on reservoirs in the Barents Sea, as well as validation of GIA model predictions using GPS and Canadian Base Network vertical motion data to determine a best-fitting model to the present-day observations. As a result of this study, it is clear that there are potential effects from GIA since the Last Glacial Maximum, and there is still vertical motion in the region meaning these effects may continue.
Co-Authorship

The thesis “Impact of long- and short-term geodynamic processes on hydrocarbon reservoirs in the Grand Banks” is a product of the research conducted solely by the author Malcolm MacDougall. Dr. Alexander Braun and Dr. Georgia Fotopoulos provided supervision, advice and editorial assistance. Dr. Alexander Braun and Dr. Georgia Fotopoulos are co-authors on all manuscripts listed below.

Manuscripts under review:

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<th>Meaning</th>
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<td>BCU</td>
<td>Base Cretaceous Unconformity</td>
</tr>
<tr>
<td>BTRT</td>
<td>Base Tertiary Unconformity</td>
</tr>
<tr>
<td>BP</td>
<td>Bonavista Platform</td>
</tr>
<tr>
<td>C-NLOPB</td>
<td>Canada-Newfoundland and Labrador Offshore Petroleum Board</td>
</tr>
<tr>
<td>CACN</td>
<td>Canadian Active Control Network</td>
</tr>
<tr>
<td>CBN</td>
<td>Canadian Base Network</td>
</tr>
<tr>
<td>CB</td>
<td>Carson Basin</td>
</tr>
<tr>
<td>CRC</td>
<td>Central Ridge Complex</td>
</tr>
<tr>
<td>CGTZ</td>
<td>Charlie Gibbs Transfer Zone</td>
</tr>
<tr>
<td>COB</td>
<td>Continent-Ocean Boundary</td>
</tr>
<tr>
<td>CBTZ</td>
<td>Cumberland Belt Transfer Zone</td>
</tr>
<tr>
<td>DTZ</td>
<td>Dominion Transfer Zone</td>
</tr>
<tr>
<td>FPB</td>
<td>Flemish Pass Basin</td>
</tr>
<tr>
<td>GSC</td>
<td>Geological Survey of Canada</td>
</tr>
<tr>
<td>GIA</td>
<td>Glacial Isostatic Adjustment</td>
</tr>
<tr>
<td>GNSS</td>
<td>Global Navigation Satellite System</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>HB</td>
<td>Horseshoe Basin</td>
</tr>
<tr>
<td>JDB</td>
<td>Jeanne d’Arc Basin</td>
</tr>
<tr>
<td>LGM</td>
<td>Last Glacial Maximum</td>
</tr>
<tr>
<td>LB</td>
<td>Laurentian Basin</td>
</tr>
<tr>
<td>LT</td>
<td>Lithosphere Thickness</td>
</tr>
<tr>
<td>LVM</td>
<td>Lofoten-Versterålen Margin</td>
</tr>
<tr>
<td>LM</td>
<td>Lower Mantle Viscosity</td>
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<tr>
<td>MIS</td>
<td>Marine Isotope Stage</td>
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<tr>
<td>NL</td>
<td>Newfoundland</td>
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<tr>
<td>NTZ</td>
<td>Newfoundland Transfer Zone</td>
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<td>OB</td>
<td>Orphan Basin</td>
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<tr>
<td>PSM</td>
<td>Petroleum Systems Modelling</td>
</tr>
<tr>
<td>TABOO</td>
<td>posT glAcial reBOund calculatOr</td>
</tr>
<tr>
<td>PL</td>
<td>Production License</td>
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<tr>
<td>PSG</td>
<td>Pseudo-Gravity Transform Filter</td>
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<tr>
<td>QC</td>
<td>Quebec</td>
</tr>
<tr>
<td>RMS/E</td>
<td>Root Mean Square (Error)</td>
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<td>SELEN</td>
<td>SEa Level EquatioN solver</td>
</tr>
<tr>
<td>SLE</td>
<td>Sea-Level Equation</td>
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<td>SDL</td>
<td>Significant Discovery License</td>
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<tr>
<td>SWB</td>
<td>South Whale Basin</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>3D</td>
<td>Three Dimensions (x, y, z)</td>
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<td>Vøring Margin</td>
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<td>---------</td>
</tr>
<tr>
<td>γ</td>
<td>Acceleration due to Gravity</td>
</tr>
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<td>α</td>
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<tr>
<td>( \lambda_a )</td>
<td>Apparent Wavelength Vector</td>
</tr>
<tr>
<td>( A_o )</td>
<td>Area of Ocean</td>
</tr>
<tr>
<td>( \Delta S )</td>
<td>Change in Relative Sea Level</td>
</tr>
<tr>
<td>( \theta )</td>
<td>Co-latitude</td>
</tr>
<tr>
<td>h</td>
<td>Cylinder Height</td>
</tr>
<tr>
<td>R</td>
<td>Cylinder Radius</td>
</tr>
<tr>
<td>( \rho )</td>
<td>Density</td>
</tr>
<tr>
<td>( \rho_i )</td>
<td>Density of Ice</td>
</tr>
<tr>
<td>( \rho_w )</td>
<td>Density of Water</td>
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<tr>
<td>( \tilde{x} )</td>
<td>Distance from end of Apparent Wavelength to Extension Axis</td>
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<tr>
<td>( S^E )</td>
<td>Eustatic Sea Level</td>
</tr>
<tr>
<td>G</td>
<td>Gravitational Constant</td>
</tr>
<tr>
<td>g</td>
<td>Gravity Anomaly</td>
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<td>S</td>
<td>Relative Sea Level</td>
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<td>U</td>
<td>Sea Floor Height</td>
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<td>Sea Surface Height</td>
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<td>( \otimes_i )</td>
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<td>( \sigma )</td>
<td>Stress</td>
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<td>( \lambda_t )</td>
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<td>( \hat{\lambda} )</td>
<td>Unit Vector in the Direction of Extension</td>
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<td>Wavelength in the Direction of Extension</td>
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Chapter 1

Introduction

1.1 Motivation

The Grand Banks is a broad region in Eastern Canada off the coast of Newfoundland (Figure 1.1), which includes the roughly 280 000 km$^2$ continental shelf of the main Grand Bank, the nearly 60 000 km$^2$ Flemish Cap to the east and the largely underexplored hyperextended continental crust of the massive Orphan Basin to the north. Water depths on the Grand Bank typically range around 200 m.

Today, the Grand Banks is best-known as a lucrative and important economic hub for Atlantic Canada, with vast and long-producing offshore oil and gas fields, most notably the well-studied Jeanne d’Arc Basin. Early exploration of the Jeanne d’Arc Basin began in the mid-20$^{th}$ century, spearheaded by both government and academic groups and the first seismic program was undertaken in 1965 by Amoco Canada Petroleum Company Ltd., while drilling commenced in 1971 (Sinclair et al., 1992; Sinclair, 1994). Presently, some 477 wells have been drilled in the Grand Banks according to the Canada-Newfoundland & Labrador Offshore Petroleum Board (C-NLOPB, 2019), and although some exploration has been conducted in other areas such as the Orphan Basin or further North on the Labrador Shelf, the most economically viable and productive region continues to be the Jeanne d’Arc Basin. The Jeanne d’Arc Basin itself is currently host to 18 fields which consist of blocks designated as Significant Discoveries, with at least a portion of 2 of those in production (Table 1.1).

It is of paramount importance to the geologists and geophysicists considering where the next well should be drilled to understand not only the long-term tectonic history of the region, and
how the trapping structures themselves were formed, but also the more recent differential viscoelastic response of the crust to Quaternary glaciations and deglaciations, which may have led to deformation of the pre-existing reservoirs. Offshore exploration is no easy or inexpensive task, so a comprehensive look at two geodynamic time scales is necessary to understand the “big picture” of the hydrocarbon accumulations and reservoirs of the Grand Banks. Long-term tectonic evolution and short-term glacial isostatic processes will be investigated herein.

1.2 Study Area Overview

1.2.1 Tectonic Evolution

Before Triassic rifting initiated the breakup of the Pangaea supercontinent in the mid-north Atlantic, the coastal margin of eastern Canada was roughly adjacent to the present-day Moroccan, Iberian and Irish margins (Ziegler, 1988; Sinclair, 1994; Welford, 2018).

The tectonic evolution of the present-day Grand Banks dates back approximately 200 ma during the Late Triassic. Through approximately 100 ma of Mesozoic rifting, many of the resultant structures are preserved in the present-day strata. Over the course of these rifting episodes, including spreading in the Labrador Sea and the opening of the North Atlantic, a complex system of hydrocarbon-bearing reservoirs was formed (Burton-Ferguson et al., 2006; Enachescu, 1987; Sinclair, 1993, 1994; Tankard et al., 1989; Van Avendonk et al., 2006; Welford et al., 2012). Although there are differences in both the structural and stratigraphic character of the various sedimentary basins located in the Grand Banks, they are typically fault-bounded and separated by pre-Mesozoic basement ridges (Enachescu & Fagan, 2004).

The Mesozoic rifting history in the currently-accepted definition is usually separated into three main phases (Sinclair, 1994; Enachescu & Fagan, 2004):

The first rifting phase – referred to as the Tethys Phase – began approximately 200 ma during the Late Triassic and lasted until the Early Jurassic. This early sequence caused roughly southwest-northeast striking rifts, splitting North America apart from Africa as well as defining many of the
basinal structures seen in the Grand Banks (Keen et al., 1990). Due to the extensional stresses oriented perpendicular to the rifting direction, blocks faulted and rotated, forming half grabens which stacked successively against larger seaward-dipping listric faults such as the Murre and Mercury (Figure 1.1), and from this the basins were formed (Sinclair, 1994; Crosby et al., 2008). Of these basins, the Jeanne d’Arc (Figure 1.2) represents the deepest extensional zone on the continental shelf, and this early rifting episode introduced clastic sediments, evaporites and basalts. Later, marine transgression in the Jurassic brought deposition of limestones, dolomites, sandstones and shales (Parnell et al., 2001; Enachescu & Fagan, 2004).
Figure 1.2. Jeanne d’Arc Basin structural overview. Notable structures include major basin-bounding Mercury, Voyager and Egret faults, regional detachment Murre Fault and underexplored Central Ridge Complex. Transect A-A’ corresponds to the cross section in Figure 1.3. Fields listed in Table 1.1 by
corresponding number. Green colour denotes Significant Discovery License (SDL), orange colour denotes Production License (PL), blue colour denotes fields where Husky Energy Inc. is operator. Adapted from Sinclair (1994) and Enachescu and Fagan (2004). Field Locations retrieved from C-NLOPB (2016).

Table 1.1. Listing of current* significant discovery licenses (SDLs) and production licenses (PLs) in the Grand Banks region with numbers corresponding to Figure 2. Information taken from Canada-Newfoundland & Labrador Offshore Petroleum Board (*C-NLOPB, 2016; 2018; 2019).

<table>
<thead>
<tr>
<th>Block Number (Figure 1.2)</th>
<th>Field</th>
<th>License Number(s) (Operator)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>North Dana</td>
<td>200A,B,C (ExxonMobil)</td>
</tr>
<tr>
<td>2</td>
<td>South Tempest</td>
<td>197 (ExxonMobil)</td>
</tr>
<tr>
<td>3</td>
<td>Trave</td>
<td>1031 (Husky Energy Inc.)</td>
</tr>
<tr>
<td>4</td>
<td>Whiterose</td>
<td>1018-1020, 1023-1030, 1043-1045, 1054 (Husky Energy Inc.)</td>
</tr>
<tr>
<td>5</td>
<td>Fortune</td>
<td>1011-1012 (Husky Energy Inc.)</td>
</tr>
<tr>
<td>6</td>
<td>West Bonne Bay</td>
<td>1040 (Equinor Canada Ltd.)</td>
</tr>
<tr>
<td>7</td>
<td>Springdale</td>
<td>1013-1014 (Imperial Oil), 1015-1017 (Husky Energy Inc.)</td>
</tr>
<tr>
<td>8</td>
<td>King’s Cove</td>
<td>1037-1039 (Suncor Energy Inc.), 1049 (Equinor Canada Ltd.)</td>
</tr>
<tr>
<td>9</td>
<td>Terra Nova</td>
<td>208A, 1050, 1053 (Suncor Energy Inc.)</td>
</tr>
<tr>
<td>10</td>
<td>Hebron</td>
<td>1006, 1046 (ExxonMobil)</td>
</tr>
<tr>
<td>11</td>
<td>Ben Nevis</td>
<td>1009, 1042 (ExxonMobil)</td>
</tr>
<tr>
<td>12</td>
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<td>1010 (ExxonMobil)</td>
</tr>
<tr>
<td>13</td>
<td>North Ben Nevis</td>
<td>1008 (Husky Energy Inc.)</td>
</tr>
<tr>
<td>14</td>
<td>South Mara</td>
<td>1003 (ExxonMobil), 1004 (Suncor Energy Inc.), 1005 (ExxonMobil)</td>
</tr>
<tr>
<td>15</td>
<td>Mara</td>
<td>1002 (ExxonMobil)</td>
</tr>
<tr>
<td>16</td>
<td>Nautilus</td>
<td>1001 (ExxonMobil), 1041 (Chevron Canada Ltd.)</td>
</tr>
</tbody>
</table>
Approximately 160 ma during the Late Jurassic, the second rifting phase initiated. This sequence is called the *North Atlantic Phase* because of the broad opening of the ocean and the separation of the Grand Banks from Iberia, and due to this, oceanic crust began to form in the mid-Atlantic (Enachescu, 1987; Keen et al., 1990; Sinclair, 1994, 1995; Braun & Marquart, 2001; Enachescu & Fagan, 2004). Due to the north-south trending rifts, along with the initiation of a potential triple-junction among oblique mid-Atlantic rift orientations, transfer faults and an associated extensional stress field striking roughly east-west were initiated, in particular reactivating the southern-bounding Egret Fault of the Jeanne d’Arc Basin. During this time, the Central Ridge complex was uplifted as a regional high (Sinclair et al., 1992). Further south, the Avalon Uplift formed through a combination of uplifting and erosional processes, providing another source of sediment for its constituent rift basins. During another period of thermal sag, the Kimmeridgian-age Egret member was deposited as part of the Rankin Formation, which represents the dominant oil-generating source rock located in the Grand Banks (Enachescu & Fagan, 2004; Baur et al., 2010). Figure 1.4 shows a cross section of the Jeanne d’Arc Basin.
Figure 1.3. Cross section from A-A‘ (Figure 1.2), of the Jeanne d’Arc Basin. Notable features include the basin-bounding Murre and Voyager Faults, pinch-and-swell of the basin and undulations of the Moho. Pre-Mesozoic formations characterized red beds, shales, ironstones, quartzarenite and a gneissic basement. Adapted from Enachescu & Fagan (2004) and Enachescu (1988).

Lastly, rifting extended in the northwestward direction, opening up the Labrador Sea during the mid-Cretaceous approximately 120 ma, in what is appropriately referred to as the Labrador Phase. Due to the oblique extension of the previously double-extended crust, a great deal of fragmentation was caused among the basins, most notably the Trans Basin Fault Zone (TBFZ) which strikes roughly northwest-southeast within the Jeanne d’Arc Basin, forming a number of important hydrocarbon trapping structures within a series of fault blocks, horsts and grabens (Enachescu & Fagan, 2004). At the same time, terracing developed along the eastern-bounding Voyager Fault and Avalon Member sandstones were deposited into the White Rose structural high (Sinclair, 1993). Following this, Albian and Aptian sandstones were deposited during a period of extensive faulting which created more trapping structures, and then overlaid by the marine shale-rich Nautilus Formation from late Cretaceous transgression (Parnell et al., 2001; Marshall, 2014). The rifts created oceanic crust north of the Charlie-Gibbs Transfer Zone (CGTZ) by 60 ma and caused initial separation of Canada from Greenland and northwest
Eurasia. However, continued rifting and the interaction with the Iceland hotspot east of Greenland caused the present North Atlantic to open as well, forcing Greenland to move back toward Canada, and closing up the Labrador rift arm around 37 ma (Keen et al., 1990; Braun & Marquart, 2001; Braun et al., 2007). The result of these closed rifts is the present day failed Labrador rift arm, which extends into Baffin Bay, and is characterized by anomalously thinned crust due to the extension (Oakey and Chalmers, 2011).

Considering the current accepted explanation of Mesozoic rifting-driven evolution of the Grand Banks, it is apparent that a majority of the geological structures located in the region are well-understood, but there is no accepted explanation for the periodic nature of some of the features seen in gravity and magnetic anomaly data. Boudinage seems to explain this phenomenon reliably well, especially considering the extensional regime during this time was suitable to produce these types of features. Since the Grand Banks is an area of significant oil and gas exploration and production, a better understanding of the mechanisms which drove the evolution is an important tool to better understand why hydrocarbons may have accumulated (or not) in the areas they are presently seen, and future exploration decisions may be influenced by this additional insight as proposed herein.

1.2.2 Quaternary Glaciation and Glacial Isostatic Adjustment

Quaternary evolution of the Grand Banks was characterized mainly by a series of glacial cycles beginning around 2.5 ma (Boellstorff, 1978; Piper, 2005). The first stage of North American Pleistocene glaciation is known as the pre-Illinoian, consisting of many separate glacial cycles ending around 300 ka. This was followed by the more well-known Illinoian (302-132 ka) and Wisconsinan (75-10 ka) glacial periods. The two most recent glacial periods were separated by
the Sangamonian interglacial period, which was characterized by warmer temperatures and relatively higher eustatic sea levels (Otvos, 2005; Person et al., 2007; Richmond and Fullerton, 1986). The Last Glacial Maximum (LGM) occurred approximately 21 ka during the Wisconsinan glaciation and was characterized by a significant eustatic sea level drop. Deglaciation likely occurred over a period of approximately 13 thousand years between 20 ka and 7 ka, which is seen by the levelling of Equivalent Sea Level rise around this time in Spada et al. (2012) and Peltier (2004).
Figure 1.4. Timeline of Quaternary glaciation in North America. Blue stages indicate glacial periods, pink stages indicate interglacial periods, and grey indicates a combination of glacial and interglacial periods. Timeline adapted from Boellstorff (1978), Richmond & Fullerton (1986) and Dyke et al. (2002). Eustatic sea level curve adapted from Otvos (2005) and Person et al. (2007). Marine Isotope Stages (MIS) from Fulton (1989). Last Glacial Maximum indicated at 21 ka.
The extent of the Laurentide ice sheet at the LGM has been a point of discussion among a number of studies over the years (Shaw & Longva, 2017). Figure 2 displays some interpretations of the ice extent at or near the LGM. Various estimates through time imply a broad trend of LGM extent extending further outboard of Newfoundland, with some recent interpretations placing the edge of the Laurentide ice sheet near the Grand Banks shelf break. One of the earliest estimates given by Prest (1969) places the sheet’s edge in a pattern of repeated lobes roughly following the coast line of Eastern Canada, with ice-free area in regions of water depths exceeding 400 m such as the Laurentian Channel. Following this however, subsequent estimates through the 1970’s and 80’s placed the limit much farther back, with some containing very little presence of sea ice (Ives, 1978; Peltier & Andrews, 1976; Quinlan & Beaumont, 1981, 1982). More recent interpretations have allowed a more generalized extent boundary, with some extending nearly to the shelf break (Peltier et al., 2015; Shaw, 2006; Shaw & Longva, 2017; Shaw et al., 2006; Tushington & Peltier, 1991; Wickert, 2016). The two extents used in modelling for this study are those of Tushington & Peltier (1991) and Peltier (2004).
Figure 1.5. Grand Banks bathymetry map with approximated LGM ice extent estimations from various authors superimposed.

1.3 Objectives

The objectives of this thesis are two-fold and aim to use present-day geophysical observations to both characterize long-term tectonic mechanisms and structures as well as validate deformation predictions from numerical models, respectively. In particular:

1. Demonstrate through geophysical observations that the long-term tectonic evolution of the Grand Banks passive margin was driven at least in part by lithospheric boudinage, and that the present-day geology is characterized by a systemic pattern of pinch-and-swell structures visible in seismic sections, as well as repeated signatures in gravity and magnetic data.

2. Through numerical modelling techniques, show that the geologically-speaking short-term effects of Glacial Isostatic Adjustment can potentially cause reservoir tilting and other
effects such as fault reactivation, opening and/or closing of fluid conduits and geochemical implications for trapped hydrocarbons.

1.4 Mathematical Methods and Modelling
Each investigation involved application of well-documented methods for purposes of data processing, enhanced interpretation or numerical simulation. Outlined here is a brief overview of some of the methods utilized which are not presented in detail within the manuscripts in Chapters 2 and 3.

1.4.1 Bathymetry Corrections for Free Air Gravity Data
Publicly available free-air gravity data from the Geological Survey of Canada (Dehler & Roest, 1998) sheds light on some of the larger anomalies present within the shelf, however when looking for general trends in wavelength value across certain transects, it is prudent to acknowledge the impact of bathymetric effects on the dataset. The Grand Banks, although generally somewhat flat and shallow (~200 m water depths), is bounded by a relatively sharp drop in seafloor elevation, in some areas this means a nearly 5 km depth increase over less than 100 km lateral distance. To account for these effects and remove them, a method using the mathematical terrain correction of Hammer (1939) and applied by Lefort et al. (1999) is described by Nowell (1999), which in effect produces a pseudo-Bouguer anomaly map for offshore regions.
Figure 1.6. Schematic of a shipborne gravity survey where measurements are taken at sea level, and impacted by depth to sea floor variability, or subsea topography. Adapted from Nowell (1999).

While the marine Bouguer correction is in principle calculated similarly to the Bouguer correction on land, the effect must be added to the free-air gravity in order to compute the Bouguer anomaly. This is due to the absence of rock beneath the gravity station. In addition, the effect of water down to the seafloor is calculated using a disk of water below the station and cylinders of increasing radius all the way down to the maximum depth – otherwise known as Hammer Zones. The formula for computing the marine Bouguer correction is given as:

\[
g = 2\pi G \rho \left( R - \sqrt{R^2 + h^2} + h \right) \tag{1.1}
\]

where the density \( \rho \) is the contrast between the Bouguer slab and water (for this investigation the values of 2670 kg/m\(^3\) and 1000 kg/m\(^3\) were used, respectively). The values for \( R \) and \( h \) were determined using the terrain correction table for gravity presented by Hammer (1939) and implemented iteratively with the radius increasing with each depth zone, until mean depth within the cylinder is the depth to sea floor. Following this, the gravity effect of each cylinder was summed and the total marine Bouguer correction at each station was added to each respective
free-air gravity value on the grid. Figures 1.6a and 1.6b display the input and output of this operation.

Figure 1.7. a: Free air gravity map without bathymetry corrections, and b: bathymetry corrected marine Bouguer gravity map following method from Hammer (1939) and Nowell (1999).

1.4.2 Spectral Analysis of Potential Field Data
Gravity and magnetic signatures in line with seismic appeared to compliment the interpreted pinch-and-swell structures, however to more effectively communicate the systemic nature of different wavelengths dominating different orientations, a spatial-domain Fourier decomposition was performed to elucidate the dominant wavelengths occurring in each of the three directions of extension for the gravity and magnetic data.

Pre-selected lines along the gridded potential field data were subjected to a Fourier transform to visualize the signal in the wavenumber domain, and the power spectral density was computed and normalized to determine the dominant wavelengths along these transects. This analysis served as an additional tool to quantify the values seen in comparison with seismic and does indeed have its potential pitfalls.

Firstly, the orientations of transects from which signals were obtained were chosen to represent a rough approximation of vectors that are positioned orthogonal to the rifting axes indicated by Enachescu (1987), Sinclair (1993) and Driscoll (1995). The precise locations of these rifting axes
leave room for some interpretation, and as such creates a potential source of error. The dominant wavelengths along these segments could vary by location, and the obvious solution would be to draw from multiple segments; however due to the fact that the rifting axes are not perfectly linear and the successive overprinting of extensional stresses in oblique orientations creates an imperfect distribution of anomaly contrasts, this would likely not produce any stronger results than just using one line in each direction.

The objective for examining power spectral density of the potential field data is to get a broad estimate of what wavelengths are dominant, although due to the reasons expressed this serves as a rudimentary quantitative support to the observed trends in signal such as density contrast – which is perhaps better viewed in context along seismic lines, or simply at the map scale.

1.4.3 Pseudo-Gravity Transform Applied to Magnetic Data

To better correlate wavelengths observed in magnetic and gravity data, a transformation as described in Baranov (1957) (see also Baranov and Naudy, 1964; Blakely, 1995; Panepinto et al, 2014) was applied to the magnetic total field intensity data in the Fourier domain. While magnetic anomalies over a magnetic body display a dipole signature, gravity anomalies over a density change display a monopole signature. In order to correlate gravity and magnetic signatures, the magnetic dipole signature is transformed into a monopole signature as if it would be a gravity anomaly, then called pseudo-gravity. The relationship between the two anomaly types can be represented as a mathematical derivative in space. The pseudo-gravity transform (PSG) is a filter which is multiplied by the wavenumber domain magnetic data and symmetrizes magnetic anomaly signals as if they were gravity anomalies for visual clarity. There are some assumptions which are made, including that the anomaly magnetization vector is oriented vertically, and the density-magnetic intensity ratio remains constant as this represents an
artificial gravity anomaly. The transformation was performed using a tool available in Oasis Montaj from Geosoft, a geoscience visualization and modelling software. In practice however, this transformation did little to support the patterns present in the actual gravity data and was not included in the manuscript presented in Chapter 2. The produced Pseudo-gravity plot is shown in figure 1.7 below.

![Figure 1.7: Pseudo-gravity plot](image)

**Figure 1.8.** **a:** Magnetic anomaly data and **b:** Pseudo-gravity transformation of magnetic anomaly data in the Grand Banks.

1.4.4 GIA Theory and Modelling

Glacial Isostatic Adjustment (GIA) or Post-Glacial Rebound as it is typically known colloquially, refers to the visco-elastic response of the Earth’s lithosphere and mantle to glacial loading hysteresis. As a result of the relatively quick response of crustal rebound and sea level change, GIA is one of the very few geological processes that is observable on a human timescale with deformation rates in excess of cm/year (Whitehouse, 2018). Since GIA is a global-scale process, it must be computed as such and considers three components in the simplest case: the solid Earth parameters and response, ice loading history and distribution and global sea load redistribution. There are two modes of isostatic bulging which arise when the Earth’s poles are loaded, one global scale which causes uplift at the equator, and one local which creates a forebulge at the periphery of the ice sheet (Figure 1.8).
**Figure 1.9.** Conceptual model of ice loads on Earth to demonstrate global and local modes of isostatic response bulging. Broad long-wavelength global bulge at the equator in response to polar loading, and short-wavelength effects at the peripherals of the ice sheets.

Before computations can be performed, it is essential to provide context for the “Sea-Level Equation”, which is the central governing equation for determining the Earth’s response to glacial hysteresis in a spherically-symmetric self-gravitating layered Earth with Maxwell rheology. Because there are two fundamental unknowns in the GIA problem – the ice loading
history and the Earth rheological parameters – the solution is non-unique and must be solved iteratively. To begin, the formula for computing relative sea level is given as:

\[ S = N - U \]  \hspace{1cm} (1.2) 

where \( S \) is the relative sea-level or depth to seafloor, \( N \) is the sea surface height and \( U \) is the sea floor height, both with respect to the centre of mass of the Earth.

The so-called “Sea-Level Equation” (SLE) first discussed by Farrell & Clark (1976) and covered by Spada & Stocchi (2007), Spada et al. (2012) and Spada (2017) is given as the change in relative sea level \( \Delta S \) with respect to changes in both the sea surface and sea floor heights, in response to ice sheet mass-balance variations as shown below:

\[ \Delta S(\theta, \psi, t) = \frac{\rho_i}{\gamma} G_s \bigotimes_i I + \frac{\rho_w}{\gamma} G_s \bigotimes_o S - \frac{\rho_i}{\gamma} G_s \bigotimes_i I - \frac{\rho_w}{\gamma} G_s \bigotimes_o S + S^E \]  \hspace{1cm} (1.3) 

The left-hand side of the equation is simply the change in water depth at some location (given by co-latitude \( \theta \) and longitude \( \psi \)) over some amount of time \( t \). On the right-hand side, the densities of ice and water are given as \( \rho_i \) and \( \rho_w \), respectively, and \( \gamma \) is the acceleration due to gravity at the surface of the Earth. \( S \) and \( I \) refer to the change in both global sea surface height and ice thickness spatiotemporally, and the operators \( \bigotimes_i \) and \( \bigotimes_o \) are spatiotemporal convolutions over the ice-covered and ocean-covered regions. \( G_s \) is the Green's function for sea-level, or simply the difference between the Green's functions for gravitational potential variation and vertical displacement.

Fundamentally, the first two terms represent the spatiotemporal variations in ice and water, and the next two terms represent the spatial average of the first two terms. These are subtracted to ensure conservation of mass, because the integration of these terms over the ocean will not necessarily have a mean of zero (i.e. not all ice melt from a sheet is added to the ocean load). The final term \( S^E \) is the eustatic sea-level variation, which can be represented
as the change in sea level over some area of ocean \((A_o)\) due to some change in ice mass \((m_i)\). The eustatic sea-level change is represented by:

\[
S^E = -\frac{m_i}{\rho w A_o}
\]  (1.4)

Equation 1.3 above is considered the gravitationally self-consistent form of the SLE, meaning that the changes in sea-level are consistent with the changes in gravitational field caused by the redistribution of surface loads on the solid Earth over the time increment \(t\) (Spada & Stocchi, 2007; Whitehouse, 2018).

This formula is especially useful for modelling applications, because assuming an ice loading history and rheological parameters for the earth model are provided as inputs, the sea-level change \(S\) can be solved for, and from here other parameters may be obtained such as the sea surface height \(N\) and the seafloor (or crustal) displacement \(U\) (Spada, 2017).

Finally, this procedure may be performed iteratively to constrain ice loading histories or rheological parameters, by comparing predicted present-day vertical crustal motion rates with observed rates from either GNSS or the combination of tide gauge and satellite altimetry data (Kuo et al., 2004; Braun et al., 2008).

1.5 Thesis Outline

The first chapter of this thesis (Introduction) provides the motivation and objectives to give rationale behind the studies completed in the following two chapters. Additionally, the introduction gives a suitable overview of the tectonic (long-term) and Quaternary (short-term) evolution of the Grand Banks of Newfoundland, as well as highlighting some of the mathematical methods and modelling techniques which are not covered in as much detail within the manuscripts. Chapters 2 and 3 are written in manuscript format, and each chapter is treated as
an independent study. Chapter 2 investigates the presence of boudinage structures in the Grand Banks using various geophysical datasets, which meets the first objective outlined in 1.2. Chapter 3 utilizes numerical modelling to simulate different isostatic responses based on a suite of 25 unique rheological models, since the Last Glacial Maximum (LGM). This chapter addresses the second thesis objective. Chapter 4 contains a discussion relating to the completion of both independent studies, and the overall implications they may have on hydrocarbon accumulations and structural deformation in the Grand Banks. Chapter 5 summarizes the main conclusions of the body of work as they relate to the research objectives and highlights recommendations for future work. The manuscripts that constitute Chapters 2 and 3 are listed below.


Additionally, this thesis is formatted such that references are listed at the end of each chapter.
1.6 References


http://doi.org/10.1126/science.202.4365.305


https://doi.org/10.1016/j.epsl.2007.07.050


http://doi.org/10.1016/j.jog.2008.03.005


Chapter 2
Evidence of Lithospheric Boudinage in the Grand Banks of Newfoundland from Geophysical Observations

2.1 Abstract
The evolution of the passive margin off the coast of Eastern Canada has been characterized by a series of rifting episodes which caused widespread extension of the lithosphere and associated structural anomalies, some with the potential to be classified as a result of lithospheric boudinage. Crustal thinning of competent layers is often apparent in seismic sections, and deeper Moho undulations may appear as repeating elongated anomalies in gravity and magnetic surveys. By comparing the similar evolutions of the Grand Banks and the Norwegian Lofoten-Vesterålen passive margins, it is reasonable to explore the potential of the same structures being present. This investigation supplements our knowledge of analogous examples with thorough investigation of seismic, gravity and magnetic signatures, to determine that boudinage structures are evident in the context of the Grand Banks. Through analysis of seismic, gravity and magnetic data, a two-layer boudinage mechanism is proposed, which is characterized by an upper crust short-wavelength deformation ranging from approximately 20 – 80 km and a lower crust long-wavelength deformation exceeding 200 km in length. In addition, the boudinage mechanism caused slightly different structures which are apparent in the block geometry and layeredness. Based on these results, there are indications that boudinage wavelength increases with each successive rifting phase, with geometry changing from domino style to a more shearband/symmetrical style as the scale of deformation is increased to include the entire lithosphere.
2.2 Introduction

The evolution of the Grand Banks region offshore Newfoundland dates back to the initial breakup of the Pangea supercontinent approximately 200 ma during the Late Triassic. Through approximately 100 ma of Mesozoic rifting, many of the resultant structures are preserved in the present-day strata. Over the course of these rifting episodes, including spreading in the Labrador Sea and the opening of the North Atlantic, a complex system of hydrocarbon-bearing reservoirs was formed (Burton-Ferguson et al., 2006; Enachescu, 1987; Sinclair, 1993; Tankard et al., 1989; Welford et al., 2012). Although there are differences in both the structural and stratigraphic character of the various sedimentary basins located in the Grand Banks, they are typically fault-bounded and separated by pre-Mesozoic basement ridges (Enachescu & Fagan, 2004).
In this paper, we analyze geophysical observations from gravity, magnetic and seismic surveys in search for evidence of boudinage features in the crust/lithosphere of the Grand Banks region. The geophysical observations are then integrated with the tectonic evolution, dominated by extensional regimes, between the Late Triassic and Late Cretaceous periods. Following this, the spectra of gravity and magnetic data are analyzed to determine the dominant wavelengths present.
in the regional structures, in order to establish the periodic nature of these wavelengths perpendicular to the rift axis.

The Mesozoic rifting history in the currently-accepted definition is usually separated into three main phases (Sinclair, 1993; Enachescu & Fagan, 2004):

The first rifting phase – referred to as the *Tethys Phase* – began approximately 200 ma during the Late Triassic and lasted until the Early Jurassic (Figure 2.2a). This early sequence caused roughly southwest-northeast striking rifts, splitting North America apart from Africa as well as defining many of the basinal structures seen in the Grand Banks (Keen et al., 1990). Due to the extensional stresses oriented perpendicular to the rifting direction, blocks faulted and rotated, forming half grabens which stacked successively against larger seaward-dipping listric faults such as the Murre and Mercury (Figure 2.1), and from this the basins were formed (Sinclair, 1993; Crosby et al., 2008). Of these basins, the Jeanne d’Arc (Figure 2.1, inset) represents the deepest extensional zone on the continental shelf, and this early rifting episode introduced clastic sediments, evaporites and basalts. Later, marine transgression in the Jurassic brought deposition of limestones, dolomites, sandstones and shales (Parnell et al., 2001; Enachescu & Fagan, 2004).

Approximately 160 ma during the Late Jurassic, the second rifting phase initiated (Figure 2.2b). This sequence is called the *North Atlantic Phase* because of the broad opening of the ocean and the separation of the Grand Banks from Iberia, and due to this, oceanic crust began to form in the mid-Atlantic (Enachescu, 1987; Keen et al., 1990; Sinclair, 1995; Braun & Marquart, 2001; Enachescu & Fagan, 2004). Due to the north-south trending rifts, along with the initiation of a
potential triple-junction among oblique mid-Atlantic rift orientations, transfer faults and an associated extensional stress field striking roughly east-west were initiated, in particular reactivating the southern-bounding Egret Fault of the Jeanne d’Arc Basin. During this time, the Central Ridge complex was uplifted as a regional high (Sinclair et al., 1992). Further south, the Avalon Uplift formed through a combination of uplifting and erosional processes, providing another source of sediment for its constituent rift basins. During another period of thermal sag, the Kimmeridgian-age Egret member was deposited as part of the Rankin Formation, which represents the dominant oil-generating source rock located in the Grand Banks (Enachescu & Fagan, 2004;).

Lastly, rifting extended in the northwestward direction, opening up the Labrador Sea during the mid-Cretaceous approximately 120 ma, in what is appropriately referred to as the Labrador Phase (Figure 2.2c). Due to the oblique extension of the previously double-extended crust, a great deal of fragmentation was caused among the basins, most notably the Trans Basin Fault Zone (TBFZ) which strikes roughly northwest-southeast within the Jeanne d’Arc Basin, forming a number of important hydrocarbon trapping structures within a series of fault blocks, horsts and grabens (Enachescu & Fagan, 2004). At the same time, terracing developed along the eastern-bounding Voyager Fault and Avalon Member sandstones were deposited into the White Rose structural high (Sinclair, 1993). Following this, Albian and Aptian sandstones were deposited during a period of extensive faulting which created more trapping structures, and then overlaid by the marine shale-rich Nautilus Formation from late Cretaceous transgression (Parnell et al., 2001). The rifts created oceanic crust north of the Charlie-Gibbs Transfer Zone (CGTZ) by 60 ma and caused initial separation of Canada from Greenland and northwest Eurasia (Figure 2.2d).
However, continued rifting and the interaction with the Iceland hotspot east of Greenland caused the present North Atlantic to open as well, forcing Greenland to move back toward Canada, and closing up the Labrador rift arm around 37 ma (Keen et al., 1990; Braun & Marquart, 2001; Braun et al., 2007). The result of these closed rifts is the present day failed Labrador rift arm, which extends into Baffin Bay, and is characterized by anomalously thinned crust due to the extension (Oakey and Chalmers, 2011).
Figure 2.2. North Atlantic Rifting Evolution. a: 200 ma b: 160 ma c: 100 ma d: 60 ma. Extensional stress directions for each rifting episode appear as double-headed arrows with colours red, yellow and blue corresponding to initial, intermediate and final rifting phases, respectively. Modified from original figure in Braun and Marquart (2001).

Considering the current accepted explanation of Mesozoic rifting-driven evolution of the Grand Banks, it is apparent that a majority of the geological structures located in the region are well-
understood, but there is no accepted explanation for the periodic nature of some of the features seen in gravity and magnetic anomaly data. Boudinage seems to explain this phenomenon reliably well, especially considering the extensional regime during this time was suitable to produce these types of features. Since the Grand Banks is an area of significant oil and gas exploration and production, a better understanding of the mechanisms which drove the evolution is an important tool to better understand why hydrocarbons may have accumulated in the areas they are presently seen, and future exploration decisions may be influenced by this additional knowledge.

2.3 Boudinage

2.3.1 Mechanism

The mechanism, “boudinage” (from French, meaning blood sausage) refers to the creation of pinch-and-swell structures within a body of varying competence. When there are layers of differing rheology – some more structurally competent than others – and a lateral stress field is applied to stretch them apart, the competent layers are transformed in ellipsoidal structures, which eventually split into discrete segments also known as boudins. They are typically more recognizable in sections which are parallel to the long axis of the boudins and may appear as a series of repeated elongate structures from above. In general, the competent layers will split by faulting or fracturing, exhibiting brittle deformation, and the surrounding incompetent layers will behave with a ductile deformation, resulting in plastic deformation and flow to occupy the space generated by brittle deformation (Fossen, 2010). From Ramberg (1955), the terms competent and incompetent are relative and generally correspond to materials which are either brittle and do not deform by plastic flow or are ductile and do deform by plastic flow, respectively.
While boudinage is often referred to the small-scale extension of rocks, for instance a granite layer stretched in a gneiss matrix, this phenomenon has been proposed for the lithospheric scale as well (Froidevaux, 1986; Ricard & Froidevaux, 1986; Braun & Marquart, 2004; Osmundsen & Ebbing, 2008; Gernigon et al., 2014; Brune et al., 2017). Passive margin formation associated with large-scale continental breakup and rifting is often considered the result of lithospheric extension (Houseman & England, 1986; Bassi, 1991). Through the use of numerical modelling techniques, it is clear that a number of parameters contribute to the formation of rifted basin and range structures within passive margins (England, 1983; Bassi, 1995; Spadini & Podladchikov, 1996), the most important of these include strain rate, the impact of thermal regime on mantle viscosity, and lithosphere thickness (Buck et al., 2003). The repetitive spacing of features which are a result of extension has been proposed to be due to lithospheric-scale boudinage mechanism (Fletcher & Hallet, 1983; Froidevaux, 1986) and localization instabilities (Montesi & Zuber, 2003). When the lithosphere is under continuous extension during rifting, large boudin-like structures may appear. Again, these could be symmetric or asymmetric depending on the stress field properties and the rheology of the lithosphere, including viscosity contrasts, deformation history, and coupling between the crust and mantle (Fossen, 2010).

2.3.2 Classification
There are a few classifications for boudinage structures which have formed under varying conditions. These are defined both by geometry and scale. According to Goscombe et al. (2004), the geometry of the boudins can be split into three main classes:

1. Shearband
2. Symmetric
3. Domino

The geometry of the boudin blocks is dependent on the nature of extension, particularly which rock layers experience the force, and in what direction. In the case of extensional margins, it has been documented that domino-shaped boudins form as a result of rotated fault blocks slipping down the large detachment faults, and the Tethys-phase Grand Banks is likely no exception (Wernicke & Burchfiel, 1982). As rifting progressed through the North Atlantic and Labrador phases, the oblique extension of the rock fabric would lead to shearband or symmetrical boudin geometries as described by Ramberg (1955), Ricard & Froidevaux (1986) and Goscombe et al. (2004). By virtue of the entire lithosphere being affected, the boudin structures would vary between multi-layer and foliation scale, as described by Goscombe et al. (2004). This is due to the complex geological history of the region, coupled with the large-scale extensional mechanisms involved with the Grand Banks evolution.

The ratio of dominant wavelength to layer thickness is approximately four (Smith, 1975, 1977; Ricard & Froidevaux, 1986; Ribeiro, 2002). It is therefore suggested that wavelengths of 100-200 km would be a strong indication of lithospheric boudinage. Slightly smaller scales would correspond to distinct intervals within the lithosphere, such as boudinage of the competent upper crust or uppermost mantle. In some cases, there may be two separate layers of boudinage within the lithosphere, as discussed by Froidevaux (1986), Zuber et al. (1986) and Braun & Marquart (2004). This is supported by the fact that the strength of the lithosphere is varied with depth, as described in Figure 2.3 below.
Figure 2.3. Idealized scheme depicting a: lithosphere competency with increasing depth, b: Strength profile redrafted with values from Kearey et al. (2009) and c: conceptual effects of boudinage in the upper crust and lower crust/upper mantle region, in an anisotropic extensional regime case.

2.3.3 Analogue Model: Boudinage in the Norwegian Passive Margin

One well-studied example of a lithospheric-scale boudinage mechanism deforming a continental margin is found in the Lofoten-Vesterålen Margin (LVM) off the coast of western Norway. According to Braun and Marquart (2004), the North Atlantic rift axis developed sometime around 60 ma in the late Cretaceous and then developed into the North Atlantic mid-ocean ridge separating Greenland from Eurasia. At the same time, this forced rifiting on the west side of Greenland in the present-day Labrador Sea to stop, resulting in a failed rift arm (Oakey & Chalmers, 2011). This is consistent with the accepted definition of the terminus of the Labrador rift phase in the Grand Banks evolution. In the north Atlantic there was both active and passive rifting impacting the Vøring (VM) and Lofoten-Vesterålen (LVM) margins, respectively. While both rifting environments produce similar features, the boudinage structures formed from passive
Rifting are used here as an analog to the Grand Banks due to the similar mechanism and resulting geological structures (van Wijk & Cloetingh, 2002; Gernigon et al., 2004; Maystrenko et al., 2018).

Bathymetric data reveals another parallel between the LVM and the Grand Banks. In both cases, the bathymetry is quite flat, ruling out the possibility of bathymetric features contributing to the presence of some repetitive gravity anomalies. Gravity data on the Norwegian shelf shows elongated structures consistent with boudinage, which are similar to the structures identified in seismic data. Hence, in this paper, gravity is also employed to identify particular scales of internal crustal structures.

Additionally, the Hornsund Fault Zone located within the Hornsund margin displays rotated fault blocks characteristic of a boudinage mechanism roughly perpendicular to the strike of late Cretaceous rifting. In addition to this, pinch-and-swell structures are visible across the Lofoton-Vesterålen Margin (LVM), which are in agreement with the wavelengths of related studies (Faleide et al., 2008). Clerc et al. (2018) showed that seismic profiles in the southwestern Barents Sea taken from 2D surveys and slices of 3D volumes provide insight into boudinage mechanisms which drove the formation of many of the structures within the coastal margin of northwestern Norway. There appear to be large-scale detachment faults that cut nearly the width of the entire crust. Additionally, there appeared to be a consistent pattern of rotated fault blocks and long wavelength Moho undulations across both the Loppa and Veslemøy highs. Since these features strike roughly west-east, this is in agreement for expected pinch-and-swell given the late Cretaceous rifting which was occurring in the North Atlantic. Finally, these findings are
validated in studies by Gernigon et al. (2004) and Clerc et al. (2018), who found that there were two layers of boudinage detected in the Norwegian margin, which further support the claim of a similar lithospheric structure in the Grand Banks.

2.3.4 Fourier Analysis to Analyse Dominant Wavelengths

To determine boudinage wavelength through gravity and magnetic anomaly data, the signals must be decomposed into the dominant sinusoidal components. The most effective method for this is by spectral analysis. Gridded spatial data were subjected to a Fourier transform as shown in Schwarz et al. (1990).

A Fast Fourier Transform algorithm was implemented to convert the non-harmonic spatial domain signal into the wavenumber domain. Before this is accomplished, constant-value vectors double the length of the input signal, are appended to each end to act as padding to reduce spectral leakage and edge effects. The value of each pad corresponds to each respective end-member value (first and last measurement). This method was numerically more effective than zero-padding the vectors to reduce edge effects.

In the wavenumber domain, a high pass filter is applied to eliminate long wavelength regional effects not due to boudinage mechanisms, typically exceeding the window-length in wavelength. Alternatively, these effects may be a result of an anomalous response in the data near the shelf break, which then causes a peak when transformed to the wavenumber domain. Following this, the signal is transformed back into the spatial domain and the periodic nature of the peaks within the signal become more apparent. To define regions in the signal which contain the boudinage
wavelengths, wavenumber and line distance are plotted in a spectrogram with hot areas corresponding to wavenumber magnitude. This can easily be converted to wavelength by taking the inverse of the wavenumber values.

2.4 Data Analysis
For this investigation, publicly sourced seismic, gravity and magnetic anomaly data were analyzed to identify evidence for boudinage mechanisms that may have caused the formation of the identified structures. The main indicators would generally consist of elongated structures striking roughly sub-parallel to the rift axis, typically characterized by density anomalies in the gravity data with corresponding pinch-and-swell structures in the seismic data. Magnetic data should complement the gravity data while also giving some indication of listric detachment faults or Moho undulations. In addition, a pattern of repetition defining a periodic nature of these features would be a strong indicator of the presence of boudinage generated structures. The Geological Survey of Canada (GSC) supplied seismic lines from the 1980’s Lithoprobe project, gravity and magnetic data, while an additional gravity anomaly map was obtained from Sandwell et al. (2014), which was mostly derived from satellite altimetry data since the 1990s. In the seismic data, we looked for direct evidence of boudinage structures by analyzing the undulations of interfaces such as the Base Cretaceous Unconformity. In the gravity and magnetic data, we analyzed the spectral content along seismic lines and in-line with the extensional axis. As datasets are not always in-line with the extension axis, an out-of-line correction was developed to estimate the true wavelengths of the geophysical signatures and is described below.

2.4.1 Out-of-Line Wavelength Corrections
Due to sparse publicly-available seismic data in the Eastern Canadian continental shelf, almost all are oblique to the extensional axis, hence, some corrections had to be made to precisely calculate the true wavelengths seen in profile which resulted from rifting episodes. The first step is to determine the angle at which individual seismic lines deviate from an imaginary line which is orthogonal to the rifting axis for any given rifting phase. The apparent wavelength interpreted from the seismic data is given by the magnitude of the vector $\vec{\lambda}_{a}$ and the angle of obliquity is denoted as $\alpha$.

The scalar projection of the apparent wavelength vector $\vec{\lambda}_{a} \in \mathbb{R}^{p,q}_{p,q}$, onto the line which traverses orthogonally to extensional structures, $\vec{\lambda} \in \mathbb{R}^{p,q}_{p,q}$, is denoted by $\vec{\lambda}_{t}$ and the magnitude of this vector is equal to the true wavelength along the transect (Perwass, 2008). Thus:

$$\vec{\lambda}_{t} = \left( \vec{\lambda}_{a} \cdot \vec{\lambda} \right) \vec{\lambda}^{-1} = \left( \vec{\lambda}_{a} \cdot \vec{\lambda} \right) \hat{\lambda} = \| \vec{\lambda}_{a} \| \cos \alpha \hat{\lambda}$$

(1)

where $\hat{\lambda}$ is defined as a unit vector in the direction of some wavelength $\vec{\lambda}$ as follows:

$$\hat{\lambda} = \frac{\vec{\lambda}}{\| \vec{\lambda} \|} \text{ and } \hat{\lambda}^{-1} = \frac{\vec{\lambda}}{\| \vec{\lambda} \|^2}$$

Alternatively, the apparent wavelength can be corrected to the true value using a simple trigonometric relationship between the apparent and true wavelength, diverging at an angle $\alpha$ (Figure 2.4).
Figure 2.4. Diagram depicting typical layout for apparent wavelength vector $\lambda_a$ observed on a seismic line that is $\alpha$ degrees oblique to the true wavelength vector $\lambda_t$ which is orthogonal to the extensional rift axis.

If $\tilde{x} = \lambda_a \sin \alpha$ and $\lambda_t^{-2} = \lambda_a^{-2} - \tilde{x}^2$, the true wavelength vector $\lambda_t$ is computed by:

$$\lambda_t = \sqrt{\lambda_a^{-2} (1 - \sin^2 \alpha)} \quad (2)$$

The magnitude of this vector is then equal to the true wavelength of boudinage orthogonal to the rift axis.

2.4.2 2D Seismic Data

Interpretation of the seismic reflection data shows that boudinage structures are evident within the subsurface, however shallow due to limitations in resolution at later times in the record (deeper). In general, they are most visible in directions sub-perpendicular to rift orientations, which would be sub-parallel to the direction of extension.

Lithoprobe line 87-2b, which corresponds to the Tethys phase rifting orientation, displays a boudin structure at the Base Cretaceous Unconformity (BCU) with a wavelength of
approximately 25 km (Figure 2.5a). Subsequent out-of-line correction did not change this due to the shallow angle (approximately 12°) that the transect forms with the Tethys extension axis.

The interpretation of Lithoprobe line segment 84-3b, which is a portion of the 84-3 line, displays features that appear to have a dominating wavelength ranging between approximately 43-50 km (Figure 2.5b). After correcting for an approximately 15° angle between this transect and the North Atlantic rifting extension axis, the range is reduced to approximately 41.5-48 km. According to the wavelength-thickness ratio of 4:1 suggested by Ribeiro (2002), the competent crustal layer in this case would have a thickness of approximately 10-12 km.

Another line which supports this pattern is the Lithoprobe 85-3 line (particularly the 3a and 3b sections in Figure 2.5c). After interpretation of the sections, it was clear that dominant wavelengths range between approximately 75-85 km. This line required slightly more correction due to the higher intersection angle of approximately 26°. After corrections, the true dominant wavelength ranges between 69-75 km, corresponding to a deformed layer thickness between 17-19 km.
Figure 2.5. Interpretation of Lithoprobe line segments and corresponding uncorrected and bathymetry-corrected free air gravity, as well as magnetic anomaly signatures along transects. Estimated observed boudinage wavelengths before corrections outlined in section 3.1. Insets display location of transects within the Grand Banks region. a: 87-2b, features aligned with extension related to the Tethys rifting phase (approximately 200 ma) b: 84-3b, features aligned with extension related to North Atlantic rifting phase (approximately 160 ma) c: 85-3a and -3b, features aligned with extension related to the Labrador rifting phase (approximately 120 ma).

In general, the seismic interpretations suggested a correlation between rifting episode and apparent structural wavelength: as line orientation rotated counter-clockwise from the Tethys rift phase to the Labrador rift phase, the boudinage wavelength increased from around 20 km to greater than 80 km (Table 2.1). This result indicates that the distance between boudins grows as they are successively extended in a counterclockwise direction, and the interpretations from seismic data seem to show this empirically.

Table 2.1. Dominant Boudinage Wavelengths Observed in 2D Seismic Data Corresponding to Each Rift Phase in the Upper Crust.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Rifting phase</th>
<th>Dominant wavelength observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW-SE</td>
<td>Tethys</td>
<td>~25 km</td>
</tr>
<tr>
<td>W-E</td>
<td>North Atlantic</td>
<td>~50 km</td>
</tr>
<tr>
<td>SW-NE</td>
<td>Labrador</td>
<td>~80 km</td>
</tr>
</tbody>
</table>

2.4.3 Free Air Gravity and Magnetic Anomaly Data

The gravity and magnetic data complement the seismic interpretation, displaying similar patterns as would be expected from a recurring boudinage mechanism oriented in a semi-rotational manner about the Grand Banks portion of the continental shelf. Figure 2.5 shows the lines interpreted in the previous section with the bathymetry-corrected free air gravity and magnetic anomaly values along the transect for comparison.
Free air gravity data was corrected for bathymetry following the cylinder method presented in Hammer (1939) and Nowell (1999), utilizing bathymetry data obtained from Smith & Sandwell (1997). This procedure removes the gravity effect caused by the bathymetry (similar to the terrain correction in gravimetry) and keeps the signals caused by subsurface density anomalies. The gravity field appears to have undulations along the transect of approximately 40 km in length, which would be slightly shorter than the apparent wavelength in the seismic data. In the case of the magnetic anomaly data, the wavelength appears to be closer to 50 km, more in line with the seismic interpretation. The interesting feature among potential field data is, in general, how closely it agrees with the seismic, with local highs appearing at structural pinches and lows along swells. The periodic nature of this data also lends to the hypothesis that the boudinage mechanism is a contributing factor to formation of these structures. Uncertainties lie in the seismic interpretation, mostly due to the processing of the Lithoprobe data. If more recent seismic acquisition and processing could be performed, or alternatively having the original 1980’s seismic reprocessed using modern methods, the uncertainty could be reduced.
Figure 2.6. 1 arc-minute resolution gravity anomaly map of the Grand Banks with elongated structures highlighted with dashed lines. Colours of lines correspond to rifting episodes indicated on the right. Bold lines indicate better qualitative fit. Basin footprints adapted from Enachescu and Fagan (2004), global gravity anomaly data from Sandwell et al. (2014).

The regional periodicity of structures mentioned earlier can best be seen in Figure 2.6. Major elongated gravity anomalies are highlighted with dashed lines, corresponding to which rifting episode these most closely correlate with. This is based on the assumption that anomalies should appear perpendicular to the direction of extension, or roughly sub-parallel to actual rift arms themselves. It should be noted that the wavelengths in this figure are quite a bit longer than seen in the other data, however this is mainly a result of the relatively coarser resolution of the map generated by Sandwell et al. (2014) compared to available seismic data.
The gravity map becomes more compelling when major Mesozoic basins are superimposed, and lines are drawn along the interbasinal regions. Qualitatively, these seem to correlate well and follow many of the same repetitive patterns.

Six lines of potential field data were extracted from grids across the Grand Banks, three from a free air gravity anomaly grid and three from a magnetic anomaly grid, provided by the GSC (Dehler & Roest, 1998; Oakey & Dehler, 1998). The resolution of the data used is 2 km, however the data was interpolated onto a 1 km grid. Lines were chosen orthogonally from the three separate rifting axes in the North Atlantic, as shown in Figure 2.7. After a Fourier analysis was performed on data along these lines (padded by end-member value for twice the profile distance on either side), dominant wavelengths between 20 and 250 km were observed. These values varied by line orientation and data type, with the shorter wavelength features dominating the magnetic signal corresponding to the Tethys phase, and moving counterclockwise, the longer wavelengths became progressively more dominant. The gravity data corresponding to the Labrador phase exhibit spikes around 16 and 45 km and otherwise very high magnitudes of >200 km wavelengths. The North Atlantic phase gravity spectra appear to indicate a number of spikes, one located just under 40 km and others ranging anywhere from 80 to 200 km. Lastly, the Tethys phase gravity data was dominated by peaks of similar magnitude ranging anywhere from 30-100 km with little sign of signals elsewhere (Table 2.2). Figure 2.8 shows the unfiltered spectral signatures for the Tethys, North Atlantic and Labrador phase gravity and magnetic anomaly data for comparison.
Figure 2.7. Overview of the magnetic anomaly signature of the continental margin of Eastern Canada centred on the Grand Banks, with successive rifting axes (solid lines) and orthogonal extension directions (dashed lines) superimposed. Magnetic data from GSC (Oakey & Dehler, 1998).
Figure 2.8. Spectral signatures of uncorrected free air gravity and magnetic anomaly data along transects corresponding to each rift phase, indicated in Figure 7 (dashed lines).
Table 2.2. Dominant Boudinage Wavelengths Observed in Potential Field Data Corresponding to Each Rift Phase.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Rifting phase</th>
<th>Dominant wavelength observed (corrected gravity anomaly)</th>
<th>Dominant wavelength observed (magnetic anomaly)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW-SE</td>
<td>Tethys</td>
<td>~30-100</td>
<td>~21-100, &gt;200</td>
</tr>
<tr>
<td>W-E</td>
<td>North Atlantic</td>
<td>~40-150</td>
<td>~10, ~75, ~150</td>
</tr>
<tr>
<td>SW-NE</td>
<td>Labrador</td>
<td>~16, ~45, &gt;200</td>
<td>~35, ~80-150, &gt;200</td>
</tr>
</tbody>
</table>

2.5 Results

Since the evolution of the Grand Banks passive margin is somewhat similar to other analogues throughout the world, many of the same extensional regime structures can be expected to appear. The key difference in the extensional tectonics is the influence of rotation of rift axes about the Grand Banks. This sequence of rifting events is well documented by Enachescu (1987), Sinclair (1994), Enachescu and Fagan (2004), and Crosby et al. (2008), however the boudinage mechanism was not suggested as a driving force causing formation of some of the structures located in the Grand Banks, and the periodic nature of these structures was not typically addressed. Combining the rifting history with some documented examples of boudinage occurring throughout the world (Froidevaux, 1986; Wernicke & Tilke, 1989; Braun & Marquart, 2004; Faleide et al., 2008; Brune et al., 2017; Clerc et al., 2018), it is reasonable to propose that the mechanism that contributed to many of the anomalies found in the Grand Banks can be explained by crustal/lithospheric boudinage.

Based on the evidence presented in the data analysis, a history of events which include boudinage as a factor can be laid out and supported by observations in seismic interpretations, free air gravity and magnetic anomalies. The seismic interpretations in Figure 2.5 clearly shows the presence of distinct pinch-and-swell structures along the roughly west-east trending line. The
true wavelength of these structures is approximately 41 km, and due to the orientation of the line, it is presumed that this is correlative to upper crustal boudinage caused during one of the later rifting episodes. The potential field data seems to complement the seismic interpretations quite well, which helps to reinforce the claim that there is a distinct repeating pattern of structural forms. Analysis of regional transects corresponding to later rifting events reveals the dominance of wavelengths in the range of 100-150 km, which supports an uppermost-mantle boudinage, developing Moho undulations. In the free air gravity data, this is evident in the visible alternating density contrasts, Magnetic anomaly data seem to match closely with gravity, although with some degree of uncertainty. The principle signatures detected in the magnetic data are along the southwest-northeast transects, corresponding to rifting during a later episode.

Based on geological knowledge of the evolution of the Grand Banks, this does not contradict earlier work, but may shed more light on the mechanisms at play. For example, early rifting caused crustal-scale boudinage, which created a series of faults within the pinch-and-swells, leading to fault block rotation after slipping down detachment faults such as the Murre or Mercury faults. Following the scheme in Goscombe et al. (2004), boudin blocks in this example would classify as domino, and certainly multi-level to foliage scale layeredness. In later episodes, the boudin shape turns to a more shearband or symmetrical shape, while maintaining the same scale, chiefly due to extension in directions oblique to initial boudinage.

In general, it appears that the wavelength of boudinage increases as line orientation is rotated counter-clockwise from the Tethys phase to the Labrador phase. The reason for this can be explained most likely by a combination of the following:
1. Longer wavelength features are likely a result of multiple successive rifting episodes, compounding the effects of deformation on the same package of rock.

2. Due to the repeated oblique extension associated with successive rifting events, the upper competent layer (upper crust) is stretched such that the dominant wavelength observed is due to undulations of the Moho, and the inferred competent layer thickness is that of the lower competent layer (uppermost mantle).

It should be noted that there are a number of wavelengths that appear in the spectra which are much greater than 100 km, with some exceeding 200 km. This is possibly explained by long-range geology or bathymetric effects. Corrections were made to the gravity data following the Hammer (1939) method applied to sea-surface surveys after Nowell (1999) to correct for the shelf-ocean transition and other bathymetric features, however it is uncertain if all larger artifacts were successfully eliminated from the data. In addition, some of the Tethys phase related features may not be easily detectable in the potential field data due to successive overprinting from later boudinage mechanisms. Furthermore, long-wavelength features in North Atlantic phase spectra relative to the Labrador phase could be a result of compounded stretching over some 40 million years, with the Labrador phase features being the most well-preserved, having no further rifting activity impacting the Grand Banks region since.

The upper competent layer consisting of the upper crust and the lower competent layer consisting of the uppermost mantle each experience the boudinage mechanism and each exhibit different wavelengths which become visible in the geophysical data. In the early stages of rifting, the shallower, short wavelength effects are dominant in the data, however these features become overprinted by deeper, longer-wavelength features from the later rifting episodes.
2.6 Conclusions

The analysis of seismic, gravity and magnetic data implies that boudinage mechanisms have contributed to the evolution of the Grand Banks and may also explain the periodic nature of many structures found in this region including basins hosting hydrocarbon reservoirs. Seismic interpretation indicates that pinch-and-swell structures exist in orientations that would be expected from classic definitions of lithospheric boudinage, and the wavelength seems to increase as orientation rotates counter-clockwise starting from the Tethys to the Labrador rift phases. This example ties well with the Norwegian passive margin, as much of the data analyzed by previous authors is complementary to the Grand Banks. Many of the same structures are present, and the signatures of seismic, gravity and magnetic data are all quite comparable.

The gravity and magnetic potential field data seem to complement the seismic interpretation, with slightly longer wavelengths. This is likely due to the relatively deep penetration compared to seismic data limited to the Base Cretaceous Unconformity, and consequently deeper undulations are detected. Combined with the relatively flat bathymetry of the Grand Banks, this data reinforces that these anomalous structures are located within the subsurface and are not simply bathymetric features. Wavelength differences are proposed to be due to either a compounded successive extension of the crust, or a system containing two separate boudinage mechanisms with the upper competent layer consisting of the upper crust and the lower competent layer consisting of the uppermost mantle. This would explain why longer wavelengths are observed from later rifting events, once the upper crust is thinned successively and the deeper features become more dominant. The results presented here are further applicable for the re-evaluation of the evolution of hydrocarbon basins in the region. This study therefore provides evidence for the existence of crustal/lithospheric scale boudinage in the Grand Banks region offshore Newfoundland.
2.7 Acknowledgments, Samples, and Data

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2.8 References


Chapter 3

Implications of Glacial Isostatic Adjustment on Petroleum Reservoirs in the Grand Banks of Newfoundland

3.1 Abstract

Glacial Isostatic Adjustment (GIA), or postglacial rebound refers to the crustal response to glacial loading and unloading processes. In this investigation, we run numerical simulations using different rheological parameters and ice loading histories to obtain models of the glacial isostatic response for the Grand Banks of Newfoundland. The objective is to assess in general the potential impact of GIA on hydrocarbon reservoirs and trapping structures in terms of tilting, deformation, fault activity or geochemical implications on the trapped fluids. Comparisons may be drawn to related studies, including analogous impacts on reservoirs in the Barents Sea, as well as validation of GIA model predictions of vertical crustal motion using GNSS and levelling networks. By running a series of GIA models, a range of vertical motion rates are output through time to determine displacement amounts, and calculations are performed on these outputs to disseminate other valuable data attributes such as the displacement gradient and differences in time and space. In general, the vertical motion rate is seen to change drastically over time for certain points, as the lag in response of regions near the ice periphery leads to a distinct pattern of uplift and subsidence. The Grand Banks generally experienced between 57 m of subsidence to 34 m of uplift since the last glacial maximum, depending on the specific location and the GIA model parameters. At the reservoir scale, model results show up to ~1.0 – 1.5 m of differential vertical displacement, which could have led to reservoir tilting or even hydrocarbon migration.
As a result of this study, it is clear that there are implications of GIA on hydrocarbon reservoirs since the Last Glacial Maximum, and these effects are ongoing.

3.2 Introduction

The evolution of the Grand Banks region offshore Newfoundland can be separated into the long-term tectonic processes that formed the rifted basin structures which today bear vast hydrocarbon reserves, as well as the more recent glaciation episodes of the Quaternary which caused warping and differential vertical crustal motion in the region.

3.2.1 Tectonic Evolution

The tectonic evolutionary processes that led to the present-day state of the Grand Banks region offshore Newfoundland initiated in the Late Triassic period and persisted for nearly 100 ma, with many of the rifted structures preserved in the present-day lithology. The Mesozoic rifting that impacted the Grand Banks can be discretized into three distinct phases, usually referred to as the Tethys, North Atlantic and the Labrador phases respectively (Sinclair, 1994; Enachescu & Fagan, 2004).

Due to extension in three distinct directions each oblique from one another, a complex system of basins was formed, with diverse faulting which include regional detachments, basin bounding and transfer faults, fragmentation and repetitive half-graben structures (Burton-Ferguson et al., 2006; Enachescu, 1987; Sinclair, 1993, 1994; Tankard et al., 1989; Van Avendonk et al., 2006; Welford et al., 2012). Due to the age of rifting episodes, synrift and post-rift sedimentation and erosional processes helped lay the foundation for the regionally-prevalent Kimmeridgian-age source rock as well as many important reservoir quality formations which have trapped the vast petroleum resources discovered and produced from the Grand Banks.
The long-term tectonic processes that split the Grand Banks away from its conjugate margins in Morocco, Iberia and Ireland created the basins presently explored and exploited (Ziegler, 1988; Sinclair, 1994; Welford, 2018); however there may be shorter-term effects within the last few million years that have acted to disturb the accumulations of hydrocarbons, specifically those processes of crustal warping and deformation in response to a series of glaciation/deglaciation periods.

3.2.2 Glacial Cycles

Quaternary evolution of the Grand Banks was characterized mainly by a series of glacial cycles beginning around 2.5 ma (Figure 3.1; Boellstorff, 1978; Piper, 2005). The first stage of North American Pleistocene glaciation is known as the pre-Illinoian, consisting of many separate glacial cycles ending around 300 ka. This was followed by the more well-known Illinoian (302-132 ka) and Wisconsinan (75-10 ka) glacial periods. The two most recent glacial periods were separated by the Sangamonian interglacial period, which was characterized by warmer temperatures and relatively higher eustatic sea levels (Otvos, 2005; Person et al., 2007; Richmond and Fullerton, 1986). The Last Glacial Maximum (LGM) occurred approximately 21 ka during the Wisconsinan glaciation and was characterized by a significant eustatic sea level drop. Deglaciation likely occurred over a period of approximately 13 thousand years between 20 ka and 7 ka, which is seen by the levelling of Equivalent Sea Level rise around this time in Spada et al. (2012) and Peltier (2004).
Figure 3.1. Timeline of Quaternary glaciation in North America. Blue stages indicate glacial periods, pink stages indicate interglacial periods, and grey indicates a combination of glacial and interglacial periods. Timeline adapted from Boellstorff (1978), Richmond & Fullerton (1986) and Dyke et al. (2002). Eustatic sea level curve adapted from Otvos (2005) and Person et al. (2007). Marine Isotope Stages (MIS) from Fulton (1989). Last Glacial Maximum indicated at 21 ka.
3.2.3 Last Glacial Maximum Conditions

The extent of the Laurentide ice sheet at the LGM has long been a topic of study (Shaw & Longva, 2017). Figure 3.2 displays some interpretations of the ice extent at or near the LGM. Various estimates through time imply a broad trend of LGM extent extending further outboard of Newfoundland, with some recent interpretations placing the edge of the Laurentide ice sheet near the Grand Banks shelf break. One of the earliest estimates given by Prest (1969) places the ice sheet’s edge in a pattern of repeated lobes roughly following the coast line of Eastern Canada, with ice-free areas in regions of water depths exceeding 400 m such as the Laurentian Channel. Following this however, subsequent estimates through the 1970’s and 80’s placed the limit much farther back, with some containing very little presence of sea ice (Ives, 1978; Peltier & Andrews, 1976; Quinlan & Beaumont, 1981, 1982). More recent interpretations have allowed a more generalized extent boundary, with some extending nearly to the shelf break (Peltier et al., 2015; Shaw, 2006; Shaw & Longva, 2017; Shaw et al., 2006; Tushingham & Peltier, 1991; Wickert, 2016). The two ice extent models used in modelling for this study are those of Tushingham & Peltier (1991) and Peltier (2004), named ICE-3G and ICE-5G, respectively. In principle, any ice loading history could be used for the modelling approach, however, the objective posed herein is to find out if there are implications of GIA on hydrocarbon reservoirs in the Grand Banks at all. Therefore, we approach the problem by using end-member models as well as models which seem to agree with in situ observations of present day vertical crustal motion, as obtained from the Global Navigational Satellite System (GNSS) and repeated levelling observations.
3.3 Glacial Isostatic Adjustment

3.3.1 Background

Glacial Isostatic Adjustment (GIA) is the long-term visco-elastic response of the Earth’s crust and mantle to loading and unloading of ice sheets (Farrell & Clark, 1976). At maximum extent of an ice sheet, GIA is characterized by large regions of depressed crust covered by the portions of the ice sheet which apply a force great enough to overcome the viscous properties of the mantle beneath it. When loaded, the viscous mantle flows away from zones of subsidence and forces outboard areas to uplift, which is commonly referred to as the forebulge. There are two modes of bulging which occur as a result of glacial loading, one global-scale bulge at the equator due to...
the bipolar depression and the other localized to the peripherals of the ice sheets (Whitehouse, 2018).

Figure 3.3 depicts a simple schematic illustrating the effects of an ice load on the lithosphere in a typical passive margin setting.

Figure 3.3. A simple schematic for crustal warping related to glacial loading in a typical passive margin setting. Flexure is characterized by alternating zone of subsidence and uplift beginning with the fully-loaded crust and ending with an anchor point far-field of loading.

Another important parameter which governs the GIA response is the mantle rheology. Determining values which are suitable for use in modelling can be done by inferring viscosity from present day vertical crustal motion rates (Ivins & Sammis, 1995; Wu and Van der Wal, 2003; Paulson et al., 2007; Wang et al., 2008; Nakada & Okuno, 2016). These rates can be constrained through a number of methods, typically GNSS, tide gauge observations, or a combination of satellite altimetry and relative sea-level change observations are used (Paulson et
Additionally, studies have been done using free-air gravity data to constrain mantle viscosity magnitudes (Wu & Peltier, 1983; Zhao, 2013). Mitrovica and Forte (1997) used a two-fold approach to estimate radial viscosity profiles, combining the long-wavelength harmonics associated with mantle convection seen in free air gravity data and the GIA response decay curve in formerly glaciated zones (Mitrovica & Peltier, 1995; Mitrovica, 1996), and inverting the data. A general trend of increasing viscosity with depth has been resolved by many authors, within a similar range of magnitudes and while many of these models predict a quite complex layering of the mantle (Mitrovica & Forte, 1997; Wolf et al., 2006; Van der Wal, 2010), the modelling in this study considers a simple two-layer mantle with no lateral heterogeneities. It must be noted that the study region most likely exhibits lateral viscosity variations due to the differences between the architecture of the Canadian shield, eastern Canadian conjugate margin and oceanic crust/mantle.

### 3.3.2 Analogues

While the implications of GIA on hydrocarbon reservoir deformation is rarely investigated, there are some useful analogs to be considered to better understand the objectives of this study. Ostanin (2015) examined the impact of glacial isostasy on hydrocarbon plumbing systems in the Barents Sea, and found that there exists the potential for hydrocarbon leakage as a response to deglaciation of the Fennoscandia ice sheet since the Last Glacial Maximum. In particular, the authors note that Petroleum System Modelling (PSM) indicates substantial leakage from Jurassic reservoirs is coincident with the timing of deglaciation episodes, and conduits are the principle means of remigration when faults are reactivated or opened as a result of isostatic adjustment. In addition, there are many pockmarks present which may be an indication of blow out pipes connected to remigration pathways.
Additionally, Braun et al. (2008) explored a number of GIA modelled predictions of present-day VM in the Great Lakes region, using tide gauge, GNSS and satellite altimetry data for validation at a number of sites. This study was conducted to determine the ability of remote sensing and tide gauge data to constrain the vertical motion (VM) predictions of 70 separate GIA models using different ice histories and earth parameters. Overall, the authors were able to reduce the original suite down to 6 best fit models, with an RMS error of 0.66 mm/a for tide gauge/altimetry observation and 1.57 mm/a for the GNSS data, meaning the observations served as an effective means of constraining the modelled predictions. We follow this approach in this study as well by comparing the GIA model outputs with in situ vertical motion rates from GNSS network solutions and repeat levelling observations.

3.4 Modelling

3.4.1 Methodology

GIA modelling was completed using the SEa Level EquatioN solver 2.9 (SELEN) developed by Spada & Stocchi (2007) and described in Spada et al. (2012). SELEN is an open-source program which numerically solves the Sea Level Equation (Farrell & Clark, 1976; Peltier et al., 1978; Wu & Peltier, 1983; Spada & Stocchi, 2006). By running the program with varying input parameters, a range of estimates for vertical crustal motion through time can be calculated (Spada, 2003). The input parameters include lithosphere thickness, mantle viscosity and ice loading history. Next, outputs may be computed assuming either a one, two or three-layer mantle (other non-consecutive values up to nine may be used, however complexity increases significantly with each added layer). The increasing complexity may yield more representative and interesting results, however for the purposes of this study, a two-layer approach consisting of an upper mantle with thickness dependent on the lithosphere, and a constant-thickness lower mantle layer was chosen.
Since the mantle is a far more complex system than is allowed by a three-layer laterally-homogeneous model, the choice was made to strike a balance between the simplest and most complex models. Viscosity values were chosen and then extended based on models from van der Wal et al. (2008) and Peltier (2004), as discussed in Braun et al. (2008), following a generalized increasing viscosity-depth relationship after Mitrovica & Forte (1997) and Nakada & Okuno (2016), and visualized in Figure 3.4. Additionally, end-member models were added to provide a greater range of solutions for larger scales. A total of 50 GIA models were produced with varying input parameters. Models A-E assumed a constant upper mantle viscosity and had a range of lithosphere thicknesses between 30 km and 150 km. Models F-J used a varying lithosphere thickness as well as a varying upper mantle viscosity. The last set of Models (K-O) assumed variation in the mantle but held lithosphere thickness constant. The rest of the models (P-AA) accounted for the remaining combinations of Earth parameters shown in Figure 3.5. Lower mantle viscosity was kept constant for all models at 2.0 x 10^{21} Pa s. The purpose of ranging the upper mantle viscosity between 0.1 and 2.0 (x 10^{21} Pa s) was to reflect the changes in the lithosphere thickness between mid-continental thick, cool crust to mid-oceanic thin, warm crust. While SELEN does factor lithosphere thickness into the computations, these effects are governed by the TABOO subroutine parameters, and in general, lateral variations in viscosity are longer-wavelength and broader, while lithosphere thickness may vary more locally.
Figure 3.4. Overview of input models for SELEN for primary sets. Uppermost rows (brown) indicate Lithosphere, middle rows (red to pink) indicate upper and lower mantle layers, bottom layers (grey) indicate core. Units of viscosity are in $10^{21}$ Pa·s.

<table>
<thead>
<tr>
<th>Upper Mantle Viscosity</th>
<th>2</th>
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<th>1</th>
<th>0.5</th>
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<td>Lithosphere Thickness</td>
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<td>150</td>
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<td>30</td>
<td>Y</td>
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<td>O</td>
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</tbody>
</table>
Figure 3.5. Overview of input models for SELEN for all sets. Units of viscosity are in $10^{21}$ Pa·s, units of thickness are in km. Models were run using both ICE-3G and -5G load histories (Tushingham & Peltier, 1991; Peltier, 2004).

SELEN computes a majority of the outputs through the use of the TABOO subroutine, which is a postglacial rebound calculator. Predefined input viscosity models are used in conjunction with the chosen (or ad hoc) ice loading history to produce a prediction of VM, sea level and geoid height changes in the present day. TABOO assumes a non-rotating, self-gravitating, spherically-symmetric Earth with a Maxwell viscoelastic rheology. Within each layer, the density, shear modulus and viscosity are assumed to remain constant. For the input viscosity profiles, the lithosphere is assumed to be perfectly elastic, and the core inviscid (Spada, 2005).

The other crucial input for modelling is the choice of an ice loading history, which varies global ice sheet thicknesses through time typically beginning at the LGM. For the purposes of this investigation, the ICE-3G and ICE-5G models were used (Tushingham & Peltier, 1991; Peltier, 2004).

Each model output consists of 21 timesteps in increments of 1 ka (20 ka to present-day) with output pixels containing their corresponding estimates for VM rate (in mm/a). Grids were generated using an equal-area icosahedral pixelization, as developed by Tegmark (1996) and discussed in Spada (2003). Following this, each pixel was integrated along its respective time series to compute total displacement since LGM. The reason for outputting the VM at every time step at each pixel is because simply using the present-day predictions is not sufficient to thoroughly estimate the total displacement of each pixel over the past 20 ka. Due to the viscoelastic response of the Earth’s crust and mantle to deglaciation, there is a significant lag
before VM rates peak followed by an attenuation over time, meaning the present-day rates alone are not representative of the VM rate at any given time since the LGM.

In addition to the integrated (or net) displacement, absolute displacements can be computed to determine the total vertical distance any given point has travelled. While the absolute displacement may actually be quite similar among adjacent points, there are potential implications on the fluid properties of the trapped hydrocarbons themselves, including subaerial or submarine exposure, the expected pressurization and charge as well as a variety of geochemical changes (Doré & Jensen, 1996).

Furthermore, two more calculations can be performed to analyze the data: The gradient of the integrated displacement, and the displacement difference between two locations, e.g. the two ends of a hydrocarbon reservoir. The former produces a map which highlights the regions of greatest change in displacement, where there is the highest potential for reservoir tilting, and the latter has consequences related to collapse of the forebulge – both in magnitude and timing.

The preceding calculations including the integrated and absolute displacements, gradient and difference are all evidence that regions outboard of the maximum ice extent can have a great impact on the deformation of traps as well as potential for fault reactivation and opening/closing of conduits affecting hydrocarbon migration.

### 3.4.2 Validation

Both the input parameters and output models may be constrained using present-day geodetic and geophysical observations, which are typically made publicly available from government data repositories. Datasets used to validate modelled results can include present-day VM estimates from GNSS via the Canadian Active Control Network and passive VM observations from the Canadian Base Network (CBN). Observations at a number of sites located in eastern Canada can
be used to tie results from models at the same or very near locations. The purpose of this validation is to better constrain which combination of earth model parameters (lithosphere thickness and rheology) best fit the present-day VM rates in the study region. Next, the root mean square error can be computed for each dataset or group of selected stations for each model to quantitatively determine the best-fit model.

Ice loading histories can be better constrained through geological evidence. As estimates of paleo-shorelines are refined, these can be used in combination with typical glacial extent indicators such as end moraines, scours and furrows. Additionally, using present-day VM observations to better constrain modelled predictions is a tool that may be used iteratively in future inversions to solve for potential ice distribution and thickness.

### 3.5 Results

In this section we address calculations performed on the outputs of the numerical models. Figure 3.6a displays the ice load in the ICE-5G history at 21 ka, which is the maximum load immediately preceding the deglaciation. The first calculation is the integrated displacement, which is computed from all time steps and the results can be assessed to determine differential vertical motion (VM) across a given distance. Next, the absolute displacement is determined to resolve total VM experienced by all points on the model. Finally, gradient and difference maps are computed to delineate regions of substantial variation in net displacement, and where the greatest amount of differential VM has occurred. The impact of GIA processes is discussed at the reservoir scale and some potential implications of differential VM on petroleum reservoirs are considered. Computations are performed primarily on the median model (H5), which represents the more recent of the two ice histories used in this study and the best qualitative fit to the validation data in this region.
While all models output varied isostatic response time series, there are some general commonalities which exist among end-members. Maximum displacement amounts, and present-day uplift rates are located in north-central North America, across a northwest-southeast region loosely bounded by Great Slave Lake to the north/west and Lake Winnipeg and James Bay to the south and east, respectively. Values ranging from approximately 10 to upwards of 20 mm/a are predicted for present day rates in this region, indicating that the area which was under the most loading is still exhibiting a significant isostatic response (Figure 3.6b). The range of maximum displacements between end-members are all greater than 1 km, with the thinnest, least viscous model predicting 1.5 km in the north-central North American region. The median model predicts up to 20 mm/a and just over 1 km of total displacement in this same region.
Figure 3.6. a: Initial ice load across North America (LGM conditions) using ICE-5G ice loading history (Peltier, 2004), b: present-day VM predictions for North America obtained from model H, and c: computed integrated vertical displacement values since the LGM. White region indicates hinge line between uplift and subsidence; dashed white line indicates 2 km ice sheet thickness extent.

In the Grand Banks these values are much smaller due to the attenuated effects of isostatic adjustment on the forebulge; however, net displacement across the Grand Banks can be calculated for any number of profiles and downscaled to any desired distance (Figure 3.6c). The modelled results still indicate a significant amount of VM that may potentially impact hydrocarbon accumulations in structural, stratigraphic or combination traps.

Additionally, absolute displacement values range between approximately 50-70 m of total VM, which could have implications on the geochemistry of trapped fluids, as well as fault reactivation, opening/closing of conduits and subsequent remigration of hydrocarbons between reservoirs.

Figure 3.7. Gradient of integrated displacement in Atlantic Canada for median model using the ICE-5G ice sheet history (Peltier, 2004).
The gradients of displacement (Figure 3.7) indicate that there is evidence of differential VM of the crust, leading to potential reservoir tilting. Across the Grand Banks, the gradient has some variability, however at the reservoir scale this is shown to be on the order of 1.1 to 1.5 m every 10 km.

Additionally, the difference between both absolute and integrated displacements is especially useful at the peripherals of maximum ice sheet extent, as this captures both the maximum drop in forebulge elevation as well as hinge line migration. In general, regions that have greater difference experienced a higher magnitude and more rapid collapse of the forebulge, which can lead to greater deformation and potential implications on hydrocarbon accumulations in these regions. Figure 3.8 displays that this effect is amplified both north and south of the Grand Banks where there is typically a higher contrast between lithosphere thicknesses over a shorter distance, however there is still a substantial amount of maximum forebulge collapse in the study area.

Figure 3.8. Difference between absolute and integrated displacement in Atlantic Canada for median model using the ICE-5G ice sheet history (Peltier, 2004). LT = 90km, UM = 1.0 x 10^{21} \text{ Pa} \cdot \text{s}, \text{LM} = 2.0 x
10^{21} \text{ Pa}\cdot\text{s}. Grand Banks difference is much lower due to the more gradual change in ice thickness, likely a consequence of the longer-wavelength change from thick-to-thin lithosphere in the region compared to areas to the North and South.

These model results are supplemented by present-day observations of geodetic data at several local sites across the Maritime provinces. Observations from the Canadian Active Control Network (using Global Navigation Satellite System (GNSS) GPS receivers) and the Canadian Base Network are used independently and in combination to validate modelled predictions (Figure 3.9). In general, the trend of VM observations seems to follow that of the median model results, with some outliers.

**Figure 3.9.** Present day VM modelled prediction quantitative best-fit models a: model I3 against GNSS observations, b: model T3 against CBN stations and c: model Q3 against all observation data.

On average, the models using the ICE-5G ice history had a lower RMSE. For CACN stations, the average RMSE for 3G models was approximately 1.91 mm/a compared to 1.70 mm/a for the 5G models. For CBN stations, this trend continued with 1.69 mm/a (ICE-3G average RMSE) and 1.60 mm/a (ICE-5G average RMSE). The average RMSE values for all stations compared with ICE-3G models was nearly 2.16 mm/a compared to approximately 1.94 mm/a (ICE-5G models). However, as shown in Figure 3.10, this does not hold true for individual models, as the best quantitative fit models for all three combinations of present-day observations are all using the
ICE-3G history. Model I3 shows the lowest overall RMSE of all models and all datasets with an RMSE of nearly 0.64 mm/a for the CACN dataset. Model T3 is the best fit for CBN data, with an RMSE of approximately 0.79 mm/a, and Model Q3 is the best fit for all datasets combined with an RMSE of approximately 1.11 mm/a. Coincidentally, Q3 is also the best fitting model for the Newfoundland and Labrador region (used observations from 15 stations only) defined by the coordinate boundaries of (46°N ≤ Latitude ≤ 57°N, 50°W ≤ Longitude ≤ 63°W).

![Figure 3.10](image)

**Figure 3.10.** Root Mean Square Error for each model generated and each combination of observed data. Black = CBN Stations, Red = CACN Stations, Green = CBN and CACN Stations, Blue = stations located within the bounds of: 46°N ≤ Latitude ≤ 57°N, 50°W ≤ Longitude ≤ 63°W. First 25 models using the ICE-3G loading history (Tushingham & Peltier, 1991), last 25 models using the ICE-5G loading history (Peltier, 2004). Highlighted Models (I3, T3 and Q3) referred to in Figure 3.9.
Lastly, there is an effect due to the lag in response of the visco-elastic Earth model to unloading, as the rate of VM varies greatly over the 21 time-steps outputted by the modelled results. For locations outboard of the LGM ice extent (specifically off the coast of Newfoundland), maximum VM rate is not reached until approximately 14 ka, depending on the rheological parameters. Figure 3.11(b-f) displays VM rates at some selected time steps (particularly every 4 ka from 16 ka to the present), and there is a pulse of high uplift which migrates northwards with ice sheet recession. This is clearly delayed as the highest rates seem to fall outside of the 2 km thickness boundary but follows the direction of thickest remaining ice as the ice sheet melts over the course of about 13 ka. By 7 ka, the ice sheet is assumed to be disintegrated in Canada, with the only notable remaining ice located in Greenland.

Figure 3.12 shows the VM curves of three separate locations across the Grand Banks region, for three separate models. The curves for “West Lithoprobe” (located near the western end of the Lithoprobe 1984 seismic transect #3, displayed in green, show the greatest maximum uplift rate, as well as the least amount of subsidence. The other two locations, “East Lithoprobe” (actually located in the Orphan Basin) and “Panther P-52” (located on the Central Ridge approximately 30 km northeast of the White Rose oilfield development) are denoted by blue and red respectively, and follow very similar curves, despite being located over 500 km apart. This is likely due to their locations being a fairly similar distance from the ice sheet extent, although there is a certain degree of error as SELEN assumes a constant lithosphere thickness with no lateral heterogeneities. The Orphan basin is characterized by hyperextended continental crust in areas thinner than 10 km, potentially driven in part by local mantle convection and thermal subsidence (Dafoe et al., 2017), while the Central Ridge group is characterized by complex fault structures, is relatively uplifted and thicker, and is composed of a combination of fragmented brittle and
ductile material including potential reservoir rock including Upper Jurassic sandstones in the
Outer Ridge region (Sinclair et al., 1992).

W. Lithoprobe is predicted to have uplifted between 22-34 m since the LGM (mean = 32 m),
while the outboard points (E. Lithoprobe and Panther) are estimated to have subsided by
anywhere from 22 m in the thick, cool end-member model to 57 m in the thin, hot end-member
(mean = 32 & 35 m). Along the Lithoprobe transect, a distance of roughly 574 km, this
represents a gradient between 61-79 m of differential VM, scaled down to 1.06-1.38 m/10km at
the reservoir scale (mean = 1.17 m/10km).

Due to this gradient, there exists the possibility that some traps have been tilted, or at least
deformed enough to affect seal integrity and result in potential hydrocarbon remigration.
Figure 3.11. Ice sheet extent and some isostatic adjustment response time steps for median model (H) with Earth model parameters LT = 90 km, UM = 1.0 x 10^{21} Pa·s, LM = 2.0 x 10^{21} Pa·s. a: ICE-5G ice load at 21 ka (Peltier, 2004), isostatic response at timesteps b: 16 ka, c: 12 ka, d: 8 ka, e: 4 ka and f: present-day (with adjusted colour scale). Dashed line in figures indicates 2 km ice sheet thickness, white region indicates VM hinge line (at or near zero uplift/subsidence).
Figure 3.12. VM curves generated for three locations (Green = near west end of Lithoprobe 84-3, Blue = near east end of Lithoprobe 84-3, Red = near Panther P-52 well) for rigid and ductile end-members and median model (Dashed line = rigid end-member model, Solid line = median model, dotted line = ductile end-member model), over 20 ka time series since LGM conditions to present day.
3.6 Conclusions

The impact of Glacial Isostatic Adjustment processes on hydrocarbon accumulations in the Grand Banks of Newfoundland has not been examined before, and while there are regions which may have experienced a higher magnitude response, the implications shown herein should not be dismissed. Due to forebulge collapse and its landward migration since the LGM, reservoirs and traps in the region experienced a variable amount of vertical motion (VM), as well as differential VM rates through time.

Present-day VM rate model predictions were compared to modern CACN (GNSS) and CBN VM observations across Atlantic Canada and represent a general agreement in VM direction and trend across the region for many models. In general, the ICE-5G models provided a better qualitative and lower average RMSE, however the ICE-3G models produced the best fitting individual models for each combination of observation datasets, with the I3, T3 and Q3 models fitting the CACN, CBN and all stations, respectively.

Through numerical modelling, we have simulated GIA over the past ~21 ka since the LGM. The Grand Banks is an interesting study area because regionally, there has likely been a combination of both uplift and subsidence since the LGM, and even today there is differential motion related to residual forebulge collapse.

Across the Grand Banks, there is a high degree of variability in integrated displacement amounts, ranging between -57 m and +34 m depending on the models chosen, resulting in gradients on the order of roughly 1 to 1.5 m at the reservoir scale (10 km). This could mean that there is possible tilt of reservoirs, or the reactivation of faults. As a consequence, conduits between reservoirs may have been opened or closed in the past 21 ka, leading to tertiary migration of hydrocarbons and other fluids.
Limitations in this study originate in the use of radially symmetric rheologies as well as a limited number of ice loading histories, however, the end-member models probably include the response of more complex rheologies. In addition, lateral viscosity variations across the study region, as they can be expected at a conjugate margin, likely increase the differential VM across the region or across a reservoir. The approach used herein is applicable to any location on Earth to estimate VM history and differential VM between any two locations. It is important to not only consider the present-day GIA model output or contemporary in situ observations, but also analyse the history of VM during the entire glacial cycle here since the LGM. GIA driven reservoir tilting, leakage and hydrocarbon migration could have taken place during critical phases of hydrocarbon generation or overlapped with tectonic events, which could have amplified the implications of GIA on hydrocarbon reservoirs in the past.

3.7 Acknowledgements

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Geophysics Society (KEGS) and the Ontario Graduate Scholarship (OGS) are gratefully acknowledged.

3.8 References


Chapter 4

Discussion

4.1 Study Objectives and Results

The studies presented in Chapters 2 and 3 were performed to provide a deeper understanding of geodynamic processes which while independently are well-understood, investigating both in combination and with reference to the Grand Banks is a novel
4.1.1 Boudinage in the Grand Banks

The first study sought to explain the regional trend of lithospheric pinch-and-swell structures in the Grand Banks, which are observed in seismic interpretations, as well as repeated anomalies in gravity and magnetic signatures. Due to the complex nature of the tectonic evolution of the margin, the continental crust was subjected to successive phases of extension through three separate rifting phases, each with lateral stresses acting on and overprinting the previous (Sinclair, 1994; Enachescu & Fagan, 2004).

In earlier studies, the rifting phases were well-defined, however there has been no mention of a connection between the stresses and the clear pattern present in geophysical data, in specific orientations favouring a direction orthogonal to each rift axis. It was proposed in Chapter 2 that this repetition with respect to stress direction is not a coincidence, but instead driven by a boudinage mechanism.

This assertion is well-supported by interpretation of the public seismic data that is available in the area, as well as patterns in the potential field data – both inline with the seismic and in regional trends. In addition, the pinch-and-swell visible in the Grand Banks agrees with features seen in analogues that are typical of boudinage, including a well-known occurrence offshore Norway (Braun and Marquart, 2004; Faleide et al., 2008).

In the Grand Banks however, it appears that the wavelength increases with each successive rifting episode, which would by definition indicate a thickening of the
competent layer directly affected by boudinage – except what is more likely is that the crust was thinned and sediment was deposited and thus the deformation surface became deeper, hence the longer wavelength in observations. By the final rifting phase, this mechanism was impacting the entire crust, which would be consistent with the data, and provide evidence for lithospheric-scale boudinage. Additionally, continuous stretching of the crust over time may separate the boudins such that the pinch-and-swell wavelength is successively longer with respect to the orientation it is observed in, increasing with counterclockwise rotation.

This study is of general interest to companies operating within the petroleum industry – specifically in exploration capacities – as this information may provide some insight into useful analogues for the Grand Banks, perhaps not often considered for exploratory purposes. Offshore Newfoundland is already regarded as a valuable and important regions for hydrocarbon exploration and production, however by linking it to boudinage, a number of connections can be made to regions that may or may not have already been considered viable or economic for oil and gas exploration, such as southwestern Africa, Uruguay and the South China and Barents Seas (Brune et al., 2017; Clerc et al., 2018).

4.1.2 Glacial Isostatic Adjustment across the Grand Banks

The objective of the second study was primarily to address the impact that GIA processes have had on hydrocarbon reservoirs since the LGM, however with this came the task of developing a suite of models which simulated different degrees of deformation in different regions based on numerous input parameter combinations. This in effect created a second objective, which was determine a best-fitting GIA model for Atlantic
Canada out of those generated in the course of the study, by utilizing present-day vertical motion observations for validation. The primary objective is a novel contribution in that it is a new application of a well-known scientific principle to an area that was subjected to some interesting geodynamic effects within the last 20 ka.

Similar to boudinage, GIA is a well-understood concept in the geosciences, however the implementations have often been either much broader-scaled or focused specifically on other regions (Braun et al., 2008; Spada & Stocchi, 2012; Ostanin, 2015). Since GIA is a global phenomenon, it is difficult to achieve an accurate present-day estimate of vertical motion rates which fits every region, however by choosing a suitable ice history and a range of realistic rheological parameters, a satisfying result can be achieved for the diverse architectures of the lithosphere. In the case of the Grand Banks, this is especially true, considering the area of interest is located entirely offshore, where vertical motion observations are nonexistent.

The study began with determining a range of suitable rheological parameters and creating a suite of viscosity models that could represent a number of different regions. The median of these models (model “H”) had parameters chosen based on the median of models developed by Peltier (2004) and van der Wal et al. (2008), as discussed by Braun et al. (2008). From here, the parameters of lithosphere thickness and mantle viscosity were extended out to include some of the more extreme end-members. After this primary set of models was created (13 unique in the primary set), the remaining 12 needed to complete a suite of 25 were run with the parameters outlined in Figure 3.6. Since these 25 models were run using both the ICE-3G (Tushingham & Peltier, 1991) and the ICE-5G (Peltier, 2004) ice histories, a total of 50 GIA models were developed during this study. It
is worth noting that the approach taken herein is not limiting the choice of rheology or ice loading history.

Since the objective of the study was to determine the impact on hydrocarbon reservoirs since the LGM, the program used for running GIA models (SELEN) was executed using a customized script which allowed for outputs of vertical motion predictions at each 1 ka timestep, 21 in total for each model produced. This allowed for visualization of the change in vertical motion rate through time, including the isostatic response lag as the ice sheet retreated, the peak motion rate and the gradual relaxation over the past ~7 ka. These points were then fit to a curve using a cubic spline in order to compute the integrated (or net) displacement and the absolute displacement. From these datasets, two more products can be derived: the gradient and the difference, which each provide their own unique addition to the investigation. Extracting the vertical motion rates for time steps prior to the present day is normally not done in GIA modeling, hence, this function had to be implemented in the SELEN code.

First of all, the integrated displacement is useful to determine where a point is located (vertically) with respect to where it was located 21 ka. For instance, if a model predicts that a point on the Grand Banks has a negative integrated displacement, this implies that that particular point has subsided since the LGM. This output is one of the most important direct model predictions of tilt. By comparing the integrated displacement of two locations some distance apart, it is possible to calculate the degree of tilt that has occurred relative to LGM conditions. It is of course useful to refer to the individual curves of the two points being compared as the relaxation histories may be different,
meaning that at some point in time the degree of tilt may have been larger or smaller than the current tilt.

Next, the absolute displacement is simply a computation of how much a point has translated vertically since the LGM. On the Grand Banks, most locations experienced a degree of uplift followed by subsidence, resulting in a general trend of negative integrated displacement. Depending on the amount of uplift and subsidence, this could have an impact on the geochemical properties of the trapped fluids, such as overpressurization, more mature than expected source rock or gas exsolution or expansion (Doré et al., 2002). Another important implication of the displacement is the models imply that the Grand Banks region has not always been a completely submarine feature. Due to crustal flexure and warping derived from numerous glacial cycles, the region is likely to have been subaerially exposed at one point or another, with potential implications on the erosion of ridge structures, deposition of sediment, charge history and preservation of hydrocarbons in the constituent basins. In other words, there may be further impacts beyond just Quaternary glaciations, with about 200 ma of tectonic evolution driving crustal instability and deformation.

The gradient was computed from the integrated displacement values to determine which regions experienced the greatest amount of change in tilt, which could factor into determining where best to analyze two points. As would be expected, the steepest gradient was in most cases near the extent of the Laurentide ice sheet, however there is likely reason to disqualify this as the sole driving mechanism. For instance, the Grand Banks had a relatively low gradient compared to the Labrador Shelf, which could be a result of less ice-crust coupling to the north due to the much more abrupt drop off the
shelf. This would mean that loading effects would have been much greater on land, and the Labrador Sea would have experienced a steeper forebulge, and thus a more rapid collapse than the Grand Banks.

Finally, the last output was the difference between displacements. This was computed by subtracting the integrated displacement from the absolute, in order to draw focus to areas outboard of the ice sheet. By performing this operation, it becomes clear where the forebulges experienced both the quickest and highest magnitude collapses, as well as regions of intense hinge line oscillation. The Grand Banks was again not as severely impacted as areas to the north and south, however there is still a significant degree of forebulge collapse magnitude over a relatively rapid time series, with some regions in the Grand Banks experiencing a drop of around 50-60 m in as short as 6-8 ka. These values indicate that the points on the Grand Banks experienced the quickest change in rate over this time span, pivoting from the maximum uplift rate to the maximum subsidence rate relatively quickly. This output provides further support that areas outboard of the ice load experienced a significant amount of motion, potentially enough to cause widespread deformation and potential implications on hydrocarbon accumulations.

For the above outputs, values were drawn from the end-members as well as the median model to simplify the solution. This provided a good range of values into which present-day values would likely fall, with expected variations based on differences in location. For model validation however, two approaches were taken: qualitative and quantitative. Qualitatively, it appeared that the median model using the ICE-5G history was a good fit to the observation data, if not better than most. In fact, this seemed to be
somewhat supported by the root mean square error (RMSE), with the average RMSE among the 5G-loaded models being much lower than the average among the ICE-3G-loaded models. Interestingly, the ICE-3G-loaded models’ present-day predictions had the lowest RMSE in each category of validation. The main contrast between the two ice histories was the distribution of the thickest ice. ICE-3G places the thickest ice at 18 ka over a region roughly defined by Hudson and James Bays, while ICE-5G pushes the thickest ice to the west, primarily trending NW-SE from Great Slave Lake to Lake Winnipeg. Most significant differences in modelled predictions could be due to the variable ice thicknesses and distributions between the two ice loading models used.

The accuracy of the models was tested by comparing to present-day geodetic observations of vertical crustal motion on land. Global Navigation Satellite System (GNSS) and Canadian Base Network (CBN) stations represent examples of active and passive control networks for measuring vertical motion. Data from the Canadian Active Control Network is obtained via GPS receivers located in stations throughout Canada, which receive continuous measurements from all satellites of the GNSS within range (Kleinherenbrink et al., 2018). Canadian Base Network data is obtained from a network of pillars which are positioned three-dimensionally using GNSS measurements and is closer to the more traditional land-based method of measuring vertical crustal motion using levelling monuments linked to tide gauge stations. Model accuracy was tested in four categories:

1. Against the Canadian Active Control Network (CACN) GNSS Satellite GPS vertical motion observations
2. Against the Canadian Base Network passive vertical motion observations
3. Against a combination of (1) and (2)

4. Against only those stations which fell into a zone defined by: 46°N ≤ Latitude ≤ 57°N, 50°W ≤ Longitude ≤ 63°W (“NL Regional” stations)

In the first category, model “I3” (LT = 60 km, UM = 0.5 x10^{21} \text{ Pa} \cdot \text{s}, LM = 2.0 \times 10^{21} \text{ Pa} \cdot \text{s}) performed best with an RMSE of 0.64. For the second category, model “T3” (LT = 120 km, UM = 0.5 \times 10^{21} \text{ Pa} \cdot \text{s}, LM = 2.0 \times 10^{21} \text{ Pa} \cdot \text{s}) had the lowest RMSE of 0.79. The final two categories were meant to define the best quantitatively fitting model of all sets, comparing against all east coast data and all region-specific data available. Model “Q3” (LT = 150 km, UM = 0.5 \times 10^{21} \text{ Pa} \cdot \text{s}, LM = 2.0 \times 10^{21} \text{ Pa} \cdot \text{s}) had the lowest RMSE in the last two categories with 1.11 and 1.69, respectively. This implies that a thicker lithosphere coupled with a less viscous upper mantle appears to be a more representative model for Atlantic Canada.

4.2 Limitations

While both studies sought to achieve the highest quality analysis, interpretation and application of methods, there are always potential pitfalls which need to be addressed. The following section will outline in brief how each study could be improved upon to more effectively achieve the outlined objectives.

4.2.1 Limitations to Boudinage Study

Since the first study is heavily reliant on the processing and interpretation of pre-existing data, the key limitation of this investigation concerns data quality. It should be
noted that public seismic data – shot during both the Lithoprobe and SCREECH campaigns of the 1980’s and early 2000’s, respectively – is quite limited (Lau et al., 2006; Welford & Hall, 2007).

In addition to this, the quality of the seismic processing would greatly improve interpretation and horizon delineation quality substantially. Since most of the processing that is currently available was performed in the 1980’s, the quality would be greatly enhanced with a publicly-available modern reprocessing.

While the seismic coverage is almost negligible compared to modern-day proprietary coverage maps, the study is aided from the orientation of the available transects. Although a larger database of public seismic data would be beneficial, and surely remove (or at least minimize) some of the out-of-line interpreted wavelength corrections, the orientation of the rifting axes provides another hurdle to reliably determine the correct dominant wavelength of pinch-and-swell structures. Plate tectonic reconstruction research can provide estimates to how the region would have looked like pre-breakup, however even in some modern reconstructions of the Grand Banks conjugate margins (Welford et al., 2012), there is still uncertainty.

Furthermore, the rift axes themselves are not perfectly linear, so for this study an approximation was taken, with three transects across the Grand Banks in approximate directions corresponding to each extensional stress orientation, specifically northwest-southeast (Tethys phase), east-west (North Atlantic phase) and southwest-northeast (Labrador phase).

Notwithstanding the above-mentioned limitations, this study still achieves the first objective listed in Section 1.3. The pinch-and-swell structures are still visible in the
seismic, and there is a clear repetitive nature of alternating anomalous structures present in the gravity and magnetic data which complements the seismic evidence. Overall, the interpretation does not suffer from axes orientation as the results show that the dominant wavelength does increase with each rifting episode, and this appears to be correlative to an upper-crust boudinage transitioning to the entire crust.

4.2.2 Limitations to Glacial Isostatic Adjustment Study

This study suffers typical limitations for any modelling-based study that utilizes observational data for validation. Some of these can include validation data availability, input parameter choices and of course computational capabilities.

First, the coverage of both CACN and CBN stations in eastern Canada is not consistent or reliable, especially when tasked with validating a model to fit a more remote locale such as Newfoundland and Labrador. For instance, in Labrador there is only one CACN station and one CBN station, which severely limits the quality of comparison for model predictions in this region, with pixel resolution just under 90 km. The modelled prediction quality will inevitably suffer due to the fact that stations and receivers are land-based, and thus far-field sea floor motion is dictated by physics, math and geological input parameters.

The geological parameters themselves, including the lithosphere thickness, mantle viscosity and number of layers) and ice load history, are all independently their own sources of error. The lithosphere thickness in the Grand Banks has high variability, with areas of the Flemish Pass under 10 km thickness as a result of volcanic underpinning. This is not helped by the fact that the program used for modelling assumes a constant-
thickness lithosphere everywhere and requires a minimum lithosphere thickness of 30 km to operate (Spada et al., 2005).

Mantle viscosity is also not very well constrained in this area. The reprieve for this error source is the simple assumption that mantle viscosity varies on a much longer wavelength laterally than lithosphere thickness, so it is likely safe to assume a constant upper mantle viscosity for most locations on the east coast. However, there are some problems when assuming only a simple 2-layer mantle as this study did. The trade-off for simplicity may sacrifice accuracy, as many viscosity models assume a 5-layer model (McConnell, 1968; Nakada & Okuno, 2016; Roy & Peltier, 2017a), while computationally, SELEN is capable of up to 9 layers.

The ice load history input presents a limitation with how much it affects the modelling process and determining ice distribution and thickness at the LGM are a constant work in progress. There has obviously been some improvement over the years as better constrained ice models are produced, however the study in Chapter 3 utilized the ICE-3G and ICE-5G models, which are now 3 and 1 version out-of-date, with the newest release in the series being the ICE-6G (Peltier et al., 2015) and likely soon to be released ICE-7G (Roy & Peltier, 2017b).

This study succeeds in accomplishing the objective listed in Section 1.3 however as two different ice loading histories are considered, and the more important mechanism driving potential reservoir deformation from GIA processes appears to be choice in rheological model. The validation of the models are performed with a dataset of 41 GNSS (CACN) stations and 31 CBN stations, which combined makes 72 total observation points for the east coast used in this study. While more points would be ideal,
the locations of these stations are somewhat strategic to constrain a good fit around highly populated areas and most coastal regions are well-populated with observations points. The recent development of GIA modeling tools enabling 3D viscosity models and not only radially symmetric models, will clearly benefit further studies as the architecture of the Grand Banks exhibits obvious lateral changes in rheology.

4.3 Implications

While both studies attempted to make an interpretation based on either existing datasets or generated numerical simulations, each focused on a different geodynamic time scale, one relatively long-term (200 ma) and other relatively short-term (20 ka), geologically-speaking. The two studies converge in two ways: They both focus on the Grand Banks, and for this reason, they both are concerned with the potential implications these geodynamic processes may have on hydrocarbon exploration and accumulation potential in the study area and in applications abroad. Similar to the objectives of this thesis, the implications are two-fold:

1. Based on a comprehensive analysis and interpretation of a suite of geophysical data including 2D seismic sections and free air gravity and magnetic anomaly maps, it is clear that there exists signatures of structures that fit the definition for lithospheric boudinage in the Grand Banks of Newfoundland. From this it may be useful to examine margins known to be associated with a boudinage mechanism driving the evolution, for the purposes of hydrocarbon exploration.
2. After generating a suite of 50 unique Glacial Isostatic Adjustment models with input parameters that may generally represent eastern Canada, it is clear that this geodynamic process has a quantifiable impact on the Grand Banks, most notably by a vertical motion differential at the reservoir scale that could have caused tilt, leakage and remigration of hydrocarbons. Additionally, the effects of GIA could have led to fault reactivation, fluid conduit opening or closing, seafloor stability issues or geochemical alterations to oil and gas contained within traps.

As a result of these studies, it is clear that the long- and the short-term timescales of the evolution of an economically important passive margin environment should be examined to form a holistic approach to better inform exploration decisions and potentially apply some of the methods discussed to regions elsewhere that are underexplored and not often considered to have the same potential.

4.4 References


Doré et al., 2002


Chapter 5
Conclusions and Future Work

5.1 Conclusions

This thesis explored the impact of geodynamic processes on hydrocarbon reservoirs and trapping features in the Grand Banks, on the timescales of both long-term extensional tectonics and short-term crustal flexure as a result of deglaciation since the LGM. The first study provides an explanation of the periodicity in observed structures and complements previous research on the Mesozoic rifting-driven margin evolution without contradicting the current accepted understanding. The second study introduced a novel application of a well-known method of study regarding GIA to examining the impact on hydrocarbon reservoirs in a region not often considered to have notable implications in this type of investigation.

In Chapter 2, several geophysical datasets were utilized to investigate the structural framework of the Grand Banks, a broad region which primarily consists of the continental shelf off the coast of Newfoundland. In this study, a repeating pattern of structural anomalies was detected firstly in seismic, then later confirmed using free-air gravity and magnetic anomaly data. The wavelengths observed in each orientation are characteristic of the accepted definition for boudinage – transitioning from upper crust to lithospheric scale – but in principle obeying the 4:1 ratio of wavelength to deformation layer thickness. Overall, the longer wavelengths seen in later rifting phases is proposed to be due in part to:
1. Successive extension in subsequent rifting phases compounding on earlier effects pulls boudins further apart and,

2. The relatively competent upper crust becomes hyperextended as a result of this overprinting effect and the signal from deeper Moho undulations becomes more dominant in the observations.

This analysis provided the evidence needed to complete the first objective of the thesis, outlined in Section 1.3.

Chapter 3 sought to examine the implications of GIA – which have been well-documented in previous research – on petroleum reservoirs in the Grand Banks, which is an uncommon application of GIA modelling methods, and the first to be employed in this region. A suite of 50 unique global GIA models were created, each encompassing 21 incremental timesteps beginning with the LGM and progressing until the present day. After calculations were performed iteratively through time for each pixel in each model, maps of integrated and absolute displacement as well as gradient and difference were generated to address the potential for differential vertical motion across the Grand Banks to tilt or deform reservoirs and breach hydrocarbon accumulations. Based on the input parameters, reservoir tilts between end-member models ranged from approximately 1-1.5 m per 10 km lateral distance compared to positions at the LGM, without considering the intermediate effects of differential rates of acceleration between positions. Qualitatively, the median model (H) appeared to be a suitable fit and the average RMSE of the models using the ICE-5G load history (Peltier, 2004) was lower than that of the models using the ICE-3G history (Tushingham & Peltier, 1991). After validating models in 4 different categories, which included against the CACN (using GNSS receivers), CBN present day
vertical motion observations, all combined observational data and only those centred primarily in Newfoundland, the lowest individual RMSE values corresponded to models I, T and Q (all using the ICE-3G load history). The second objective outlined in Section 1.3 was achieved in this study, as it was determined that across all models differential vertical motion in the Grand Banks has had a significant enough influence since the LGM to potentially deform, tilt or reactivate faults which all could lead to hydrocarbon spill and remigration between traps.

In tandem, both studies contribute to the overall goal of the thesis: providing insight into both long- and short-term geodynamic processes throughout the evolution of the Grand Banks passive margin and assessing how these may have impacted hydrocarbon reservoirs. The results of both studies are applicable to other regions and this analysis may be used as a tool in future exploration programs to locate potential fields and optimize hydrocarbon recovery in regions that have been significantly impacted by glacial isostatic adjustment.

5.2 Future Work

Both studies may be used jointly in future work in the field of GIA modelling. This is achieved by developing a complex Earth model with lateral variations in lithosphere thickness and mantle viscosity (although the latter may not be as important as the former). A key limitation mentioned in Section 4.2.2 is that the software used for modelling assumes a constant-thickness lithosphere while in reality this is not representative of a coastal region like Atlantic Canada. Long-wavelength changes in values of parameters like mantle viscosity would not have as much of an impact on
isostatic response in the near-field compared to high-frequency changes in lithosphere thickness over distances sometimes as small as 100’s of kilometers.

Another pursuit that could potential come from this work is the improvement of an ice loading history. While this is actively being researched, many new ice models are developed by inverting GIA vertical motion predictions to constrain the thickness and distribution of LGM ice sheets. Because the GIA problem has two input parameters which are generally poorly constrained (ice history and Earth model), by keeping the earth model constant, the output of a GIA model could be back-calculated programmatically to achieve estimates of LGM glacial distribution and thickness.

Overall, the results of these studies define some interesting implications for hydrocarbon exploration. Two different geodynamic time scales are analyzed to show that tectonic evolution and glacial isostasy play roles in the formation and deformation of hydrocarbon-bearing reservoirs and traps, which can be assessed in present-day geophysical and geological datasets. It is of crucial importance that operators are aware of the long and short-term effects that geodynamics can have on regions which are economically productive. For instance, this study may have potential to minimize risk of drilling dry wells caused by leakage and subsequent migrations of hydrocarbons, which as a dynamic process, would not typically be clear based on the geology alone.
Appendix A
Description of Programming Scripts

A.1 Matlab Scripts

Script Name: grav_code.m

Process Description: Computes gravity corrections for bathymetry based on the method described in Section 1.4.1

Input Variable(s): Bathymetry Grid (X, Y, m depth to sea floor), Free Air Gravity Anomaly Grid (X, Y, mGal), Density of Water (1000 kg/m³), Density of Crust (2670 kg/m³), Hammer Zones defined in Hammer (1939) and Nowell (1999)

Output Variable(s): Marine Bouguer Gravity Anomaly Grid (X, Y, mGal)

Script Name: Coordinate_Transform.m

Process Description: Transforms coordinates from Latitude/Longitude (WGS-84 reference ellipsoid) to XY coordinates (UTM-22N) and vice versa for consistency/compatibility across programs

Input Variable(s): Latitude/Longitude coordinates from any grid dataset (degrees)

Output Variable(s): XY coordinates (m from UTM reference)

Script Name: Boud_Test.m

Process Description: This code is intended to take potential field data (grav or mag) along a transect of which the total line distance is known and perform Fourier Analysis on said signal to elucidate the constituent dominant wavelengths. Spectra are plotted against normalized magnitude to find peaks

Input Variable(s): Gridded potential field data (X, Y, Z), Extracted Signal Length (m)
Output Variable(s): Spectra (k [wavenumber] inverse to wavelength), plotted Power Spectral Density

Script Name: Potential_Field_Plotting.m

Process Description: Plot potential field data (gravity, magnetics) along seismic transects

Input Variable(s): Potential field data vector (X, Y, Z), Extracted Signal Length (m)

Output Variable(s): Plots of potential field data to be visualized along seismic profiles

Script Name: VM_Gradient.m

Process Description: Loads SELEN output model timesteps, organizes into matrices for each GIA model, performs computations outlined in Section 3.4.2, plots models for visualization

Input Variable(s): SELEN-output .dat files (lon, lat, mm/a), e.g. urate_MMXN_Zka.dat where X = Model Letter Identifier (A – AA, not incl. C or M), N = ice history (3 or 5), Z = timestep (20-0 ka), VM Observation Data (lon, lat, mm/a)

Output Variable(s): Any desired plot of the input models (present-day, historical, displacements, gradients, differences) as well as statistics

A.2 UNIX/BASH Scripts

Script Name: run_models

Process Description: Automate the SELEN numerical modelling software, set earth parameters and ice load history with respect to Figure 3.5. Calls stream editor (sed) utility to change parameters in the SELEN Fortran 90 source scripts

Input Variable(s): Rheological Model (includes LT, UM and LM), ice_load (.dat file with variable number of columns depending on the model used (28 for ICE-3G, 26 for ICE-5G)
Output Variable(s): Vertical Motion predictions at every timestep \((n = 21)\) for every model \((n = 50)\) for a total of 1050 output .dat files

Script Name: rename_all_files

Process Description: Rename and reorganize model files into formats which are easily understood: i.e. udotmap.dat \(\rightarrow\) urate_MMA3_0ka.dat

Input Variable(s): GIA model timesteps which are automatically output in named directories within CentOS

Output Variable(s): A directory for each model, with 18 (or 21) .dat files all names respective to their corresponding model and timestep.
Appendix B
Additional Figures

Figure B.1. Extension of Figure 1.7, with a: magnetic anomaly map of the Grand Banks and three orientations referring to extension directions (line A, B, C respectively) superimposed, b: pseudo-gravity transformed magnetic anomaly data with the same lines superimposed, c: magnetic anomaly and pseudo-gravity data along each transect plotted to show differences in wavelengths, and d: power spectral density of pseudo-gravity transformed magnetic anomaly data indicating a general trend of increasing wavelength from line A to line C.
Figure B.2. Magnetic anomaly and pseudo-gravity transformed magnetic data plotted together along each transect from Figure B.1. *Enlarged version of B.1(c).
**Figure B.3.** Power spectral density of pseudo-gravity data presented in Figure B.1 indicating a trend of increasing wavelength with orientation, beginning with Tethys and rotating counterclockwise towards Labrador phase extension. *Enlarged version of B.1(d).*

![Relative Elevation/Sea Level for White Rose (Best Fit Model)](image)

**Figure B.4.** Relative elevation and sea level curves for a point near the present-day Whiterose oil field (operated by Husky Energy) indicating subaerial exposure as recent as ~10 ka.
Figure B.5. Ice thickness at 18 ka according to the ICE-3G model (Tushingham & Peltier, 1991).

Figure B.6. Ice thickness at 18 ka according to the ICE-5G model (Peltier, 2004).
**Figure B.7.** Integrated (net) vertical displacement gradient for model “C5” (H5 parameters) for North America.
Figure B.8. Derived approximate paleo-shoreline (if ice were removed) by following the method shown in Figure B.4 at 21 ka. Change in relative sea level (RSL) is subtracted from paleo-elevation modelled prediction to obtain the paleo-shoreline. Boxes along lines point down-dip to regions that would have been submarine.