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

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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 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 in the Norwegian Margin and the South China Sea with a 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 geophysical data (including seismic, gravity and magnetic observations), a multi-stage 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.

Keywords: geophysical interpretation; passive margin evolution; seismic interpretation; boudinage; grand banks; extensional tectonics

1. Introduction

The evolution of the Grand Banks region offshore of Newfoundland (Figure 1) dates back to the initiation of the 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 [1–5]. 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 [1–4,6]. 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 basement ridges [5]. Geophysical datasets—including 2D seismic, magnetic anomaly and free-air gravity anomaly—display some repetitive anomalous features both in geometry and material property that could be indicative of a boudinage mechanism impacting the tectonic evolution of the region.
In this paper, we analyze geophysical observations from gravity, magnetic and seismic surveys to determine if there is quantitative or qualitative 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. Moreover, there are a number of well-studied examples of rift margin evolution with demonstrated and analogous boudinage mechanisms such as in the Norwegian Shelf and the South China Sea [7–9].

The Mesozoic rifting history, according to the currently-accepted definition, is usually separated into three main phases [2,5]:

The first rifting phase—referred to as the Tethys Phase [1,2,5]—began approximately 200 Ma during the Late Triassic and lasted until the Early Jurassic (Figure 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 [10]. 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), and from this the basins were formed [2,11]. Of these basins, the Jeanne d’Arc (Figure 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 [5,12].

Approximately 160 Ma during the Late Jurassic, the second rifting phase initiated (Figure 2B). This sequence is called the North Atlantic Phase [1,2,5] 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 \cite{1,5,10,13,14}. Due to the north-south trending rifts, along with the initiation of a potential triple-junction \cite{15} 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 \cite{16}. 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 \cite{5}.

![Figure 2. North Atlantic Rifting Evolution.](image-url)  
(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 colors red, yellow and blue corresponding to initial (Tethys), intermediate (N. Atlantic) and final (Labrador) rifting phases, respectively. Light blue regions represent the proto-Atlantic opening up. Redrafted from original figure in \cite{14} with arrows added.

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 \cite{1,2,5} (Figure 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 \cite{5}. At the same time, terracing developed along the eastern-bounding Voyager Fault and Avalon Member sandstones were deposited into the White Rose structural high \cite{2}. 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 [12]. 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 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 [11,14,17]. 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 [18].

For a thorough comparison to be made, extensional tectonics associated with North Atlantic rifting should also be briefly discussed in the context of the conjugate Iberian margin. Ref. [15] discusses the Bay of Biscay triple junction, which ties into the Iberian margin crust, as there is a large failed rift arm which cuts perpendicular to the margin. North Atlantic phase rifting would have caused stretching both sub-parallel and sub-perpendicular to the margin as both rift arms would have been propagating around the same time, so it is reasonable to expect that the post-rift structures would be different, as orientation was different. [11] acknowledges asymmetry between the structural character of the conjugate margins, however noting that the lithospheric stretching may have been mostly uniform between the two, implying observed differences in the margins perhaps are due to either prior orogenic events or rift geometry.

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 may potentially 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. Boudinage

2.1. Mechanism

The mechanism, “boudinage” (from French, meaning blood sausage) [19,20] 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 [20]. From [19], 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 often refers 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 [9,21–24]. Passive margin formation associated with large-scale continental breakup and rifting is considered the result of lithospheric extension [8,25–27]. Through the use of numerical modelling techniques, it is clear that a number of parameters contribute to the formation of rifted extensional tectonic structures within passive margins [28–31]; the most important of these include strain rate, the impact of thermal regime on mantle viscosity, and lithosphere thickness [32]. The repetitive spacing of features which are a result of extension has been proposed to be due to lithospheric-scale
boudinage mechanism [21,33] and localization instabilities [34–36]. 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 [20]. Additionally, continuous extension can lead to mantle exhumation and serpentinization [37].

Experimental lithospheric extension models [38] show that periodic instabilities in the crust during wide rift extension at wavelengths on the same order as crustal thickness produce grabens spaced regularly, and as a result produce alternating zones of deformation at a wavelength on a lithospheric scale. Ref. [39] finds that non-volcanic passive margin deformation depends on the presence of a relatively strong upper mantle, and a process of necking and boudinage at this scale for other layers within the lithosphere to continue extending.

Additionally, structural inheritance of shear zones at lithospheric and smaller interval scales was considered as a factor in further lithospheric extension [40]. Ref. [41] notes that magma-poor margins such as the Iberia-Newfoundland conjugate margins do not display introduction of igneous material until the crust has already been thinned, and usually are the result of mantle exhumation and serpentinization, both of which are commonly associated with boudinage mechanisms. Model results propose that the properties of inherited structures pre-rift determine whether a passive margin will become magma-rich or -poor following breakup. In the Newfoundland-Iberia case, the crust is generally thin, and as a result the margins are magma-poor.

Another finding of this study is that due to the complexity of inherited structures from any number of previous orogenic events in the Newfoundland margin—such as a fossil mantle wedge—prior model predictions were not as effective at elucidating the processes which lead to a hyperextended continental margin, such as the Orphan basin. In [41], hyperextension was associated with pre-existing orogenic serpentinization and thinner crust tracks with observations of lack of pre-rift magmatism, mantle exhumation and extensional allochthons, making these findings significant. Inherited structures likely impact the extension mechanics [42], although these are only partially-controlling features, as there is some influence by the rheological properties and thickness of the competent layer. A possible compromise here is that inherited structures impact the uniformity of boudinage structures, rather than the actual formation [11]. Ref. [11] also suggests that the main controls depend on the stage of extension, and the thickness of the crust. The thicker the crust, the more strain is felt by the lithospheric mantle, and conversely in thin-crust settings, the crust itself is subjected to a majority of strain.

Extensional processes at passive margins—regardless of whether boudinage is involved—are clearly influenced by the pre-existing structures from former tectonic events in the area [40]. Pre-existing weak zones or faults may be more prone to continuous extension and therefore could promote the development of boudins locally. However, the wavelength of boudinage structures is still largely controlled by the thickness of the competent layers and the current rheology. There is strong evidence that prior modifications in rheology and structure influence ongoing extensional tectonics [11,42].

2.2. 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 [43], the geometry of the boudins can be split into three main classes:

- Shearband
- Symmetric
- 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 [8], and the Tethys-phase Grand Banks is likely no exception [44]. 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 [19,22,43]. By virtue of the entire lithosphere being affected, the boudin structures would vary between multi-layer and foliation scale, as described by [43]. 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 [22,45–47]. 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 [7,21,48]. This is supported by the fact that the strength of the lithosphere is varied with depth, as described in Figure 3 below.

Figure 3. Idealized scheme depicting (A) lithosphere competency with increasing depth, (B) Strength profile redrafted with values from [49] and (C) conceptual effects of boudinage in the upper crust and lower crust/upper mantle region, in an anisotropic extensional regime case.

2.3. 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 [7], the far 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, forming the present-day Norwegian Sea. At the same time, this forced rifting on the west side of Greenland in the present-day Labrador Sea to stop, resulting in a failed rift arm [18]. 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 [9,50,51].

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 Lofoten-Vesterålen Margin (LVM), which are in agreement with the wavelengths of related studies [32]. Ref. [53] 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 [9,53], 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.

3. Data Analysis and Results

For this investigation, seismic, gravity and magnetic anomaly data obtained from the Geological Survey of Canada (GSC) [54–56] as well as a gravity anomaly map from [57] 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. 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 in Section 3.2.

3.1. 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 and the spectra may then be analyzed. Gridded spatial data were subjected to a Fourier transform as shown in [58].

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 250 km high pass filter is applied to eliminate long wavelength regional effects not due to boudinage mechanisms, typically exceeding the window-length in wavelength and primarily due to the large depth contrast introduced by the shelf break. 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.
3.2. 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 $\vec{\lambda}_a \in \mathbb{R}^1_{p,q}$ onto the line which traverses orthogonally to extensional structures, $\vec{\lambda} \in \mathbb{R}^1_{p,q}$, is denoted by $\vec{\lambda}_t$ and the magnitude of this vector is equal to the true wavelength along the transect [59]. Thus:

$$\vec{\lambda}_t = \left( \vec{\lambda}_a \cdot \hat{\vec{\lambda}} \right) \hat{\vec{\lambda}} = \left( \vec{\lambda}_a \cdot \hat{\vec{\lambda}} \right) \hat{\vec{\lambda}} = \vec{\lambda}_a \cos \alpha \hat{\vec{\lambda}}, \quad (1)$$

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

$$\hat{\vec{\lambda}} = \frac{\vec{\lambda}}{\lambda} \quad \text{and} \quad \hat{\vec{\lambda}}^{-1} = \frac{\vec{\lambda}}{\lambda^2} \quad (2)$$

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 4).

![Diagram](image)

**Figure 4.** Diagram depicting typical layout for apparent wavelength vector ($\vec{\lambda}_a$) observed on a seismic line that is “$\alpha$” degrees oblique to the true wavelength vector ($\vec{\lambda}_t$) which is orthogonal to the extensional rift axis.

If $\vec{x} = \vec{\lambda}_a \sin \alpha$ and $\vec{\lambda}_t^2 = \vec{\lambda}_a^2 - \vec{x}^2$, the true wavelength vector $\vec{\lambda}_t$ is computed by:

$$\vec{\lambda}_t = \sqrt{\vec{\lambda}_a^2 \left( 1 - \sin^2 \alpha \right)} \quad (3)$$

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

3.3. 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 is angled roughly orthogonal to the Tethys phase rifting orientation (Figure 5A, inset), displays a boudin structure at the Base Cretaceous Unconformity (BCU) with a wavelength of approximately 25 km (Figure 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.
Figure 5. Cont.
Figure 5. Interpretation of Lithoprobe line segments [54–56] and corresponding uncorrected (dashed, blue lines) and bathymetry-corrected (solid, blue lines) free air gravity, as well as magnetic anomaly (red) signatures along transects. Estimated observed boudinage wavelengths before corrections outlined in Section 3.2. 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).

The interpretation of Lithoprobe line segment 84-3b, which is a portion of the 84-3 line (Figure 5B, inset), displays features that appear to have a dominating wavelength ranging between approximately 43–50 km (Figure 5B). After correcting for approximately 15° 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 [47], 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 5C, inset). 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.

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

| Orientation | Rifting Phase | Dominant Wavelength Observed |
|-------------|---------------|-----------------------------|
| NW-SE       | Tethys        | 25 km                       |
| W-E         | North Atlantic| 50 km                       |
| SW-NE       | Labrador      | 80 km                       |

3.4. 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 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 [60,61], using bathymetry data obtained from [62]. 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, thus calculating the marine Bouguer anomaly. 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 if the original 1980’s seismic was reprocessed using modern methods, the uncertainty could be reduced.

The regional periodicity of structures mentioned earlier can best be seen in Figure 6. Major elongated gravity anomalies are highlighted with dashed lines, corresponding to which rifting episode they 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 [57] 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 [63,64]. 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 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 have very high magnitudes of >200 km wavelengths. The North Atlantic phase gravity spectra appears 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. These findings are summarized in Table 2. Figure 8 shows the unfiltered spectral signatures for the Tethys, North Atlantic and Labrador phase gravity and magnetic anomaly data for comparison.

Figure 6. 1 arc-minute resolution gravity anomaly map of the Grand Banks with elongated structures highlighted by dashed lines spaced 50 km apart. Colors of lines correspond to rifting episodes indicated on the right and are parallel to each rift axis orientation. Bold lines indicate better qualitative fit. Basin footprints adapted from [5], global gravity anomaly data from [57].

Figure 7. Overview of the magnetic anomaly signature of the continental margin of Eastern Canada centered on the Grand Banks, with successive rifting axes (solid lines) and orthogonal extension directions (dashed lines) superimposed. Magnetic data from GSC [64].
Table 2. Dominant Boudinage Wavelengths Observed in Potential Field Data Corresponding to Each Rift Phase.

| Orientation | Rifting Phase | Dominant Wavelength Observed (Corrected Gravity Anomaly) | Dominant Wavelength Observed (Magnetic Anomaly) |
|-------------|---------------|--------------------------------------------------------|-------------------------------------------------|
| NW-SE       | Tethys        | ~30–100 km                                             | ~21–100, >200 km                                |
| W-E         | North Atlantic| ~40–150 km                                             | ~10, ~75, ~150 km                               |
| SW-NE       | Labrador      | ~16, >45, >200 km                                     | ~35, ~80–150, ~200 km                           |

Figure 8. Spectral signatures of uncorrected free air gravity (A) and magnetic anomaly (B) data along transects corresponding to each rift phase, indicated in Figure 7 (dashed lines).
4. Discussion

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 [1,2,5,11], 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 [7,8,21,24,52,53,65], 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 5 clearly show 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 [43], 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:

- Longer wavelength features are likely a result of continued stretching through multiple successive rifting episodes, compounding the effects of deformation on the same package of rock.
- 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 (relatively brittle 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 [60] method applied to sea-surface surveys after [61] 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.

Although structural inheritance provides explanation for non-uniform deformation via localized instabilities and weak zones [42], the dominant wavelengths of boudinage at the scales observed herein are primarily controlled by competent layer thickness and rheological properties of the rock fabric at the initiation of extension [11].

5. Conclusions

The analysis of seismic, gravity and magnetic data indicates that a multi-stage boudinage mechanism has possibly 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. Structural inheritance was determined to possibly have local impact on boudins, however at the lithosphere scale it likely did not present any significant relation to boudinage-style deformation wavelengths. 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 compares well with the evolution of the Norwegian passive margin and the northern continental margin of the South China Sea, as much of the data analyzed by previous studies is complementary to the Grand Banks. Among several of these passive margins, the relationship between layer thickness and wavelength of boudinage are similar and the signatures of seismic, gravity and magnetic data are all 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 suggests the existence of crustal/lithospheric scale boudinage in the Grand Banks region offshore of Newfoundland.

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