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

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Summary

The goals of this study are twofold; i) To shed light on the tectonic evolution of the Grand Banks, and ii) the potential contribution of Glacial Isostatic Adjustment on reservoir titling. The evolution of the Grand Banks of Newfoundland was characterized by a series of successive rifting episodes, resulting in lateral extension in three distinct directions, with the effects compounding on one another. It is proposed that this long-term extensional regime created structures that are consistent with the well-documented phenomenon of lithospheric/crustal boudinage, which typically features boudin blocks with a wavelength four times the competent layer thickness. Across the Grand Banks, this mechanism is seen to operate at two levels, one contained in the competent strata of the upper crust, and the other much deeper in the relatively brittle uppermost mantle. As a result of this, there are regions of alternating density particularly in the upper crust, which aligns well with known locations of sedimentary hydrocarbon-bearing basins, as well as a signature of an undulating Moho surface, which is consistent with interpretations of the passive margin structure off the coast of Newfoundland.
Glacial Isostatic Adjustment (GIA) sometimes referred to as Postglacial Rebound, is the visco-elastic response of the Earth's crust to a process of loading and subsequent unloading of ice sheets. This investigation aims to determine the potential impact of glacial loading hysteresis on well-known hydrocarbon reservoirs located offshore Canada's east coast. Existing models of Glacial Isostatic Adjustment are used in conjunction with present-day geophysical observations to simulate differential vertical crustal motion rates across the Grand Banks through time. From here, assessments are made to quantify regional tilt angles and narrow the search to the reservoir scale. Finally, geophysical and geological structures are analyzed for signatures of differential vertical motion to validate modelled results and assess the potential of such processes leading to reservoir tilting and fluid migration.

Methodology

A suite of publicly-available 2D seismic, gravity and magnetic was utilized to interpret the geological structures as well as boudinage structures across the Grand Banks. Schlumberger Petrel was used for interpretation of seismic and potential field data, while Matlab was exploited for spectral analysis along profiles.
GIA has been considered a driving force behind hydrocarbon leakage among traps off the coast of Norway, mainly as a result of rapid differential uplift and erosional processes during deglaciation in Fennoscandia (Kjemperud and Feldskaar, 1992; Fjeldskaar and Amantov, 2015; Ostanin, 2015; Ostanin et al, 2017). In the Grand Banks of Newfoundland however, this has not been cited as a potential source of hydrocarbon spill among the long-producing oilfields of the Jeanne d'Arc and other regional basins, which would have been subject to some degree of uplift associated with Laurentide ice sheet recession since the Last Glacial Maximum, approximately 22 ka BP (Enachescu, 1987; Sinclair, 1994; Crosby et al, 2008).
A suite of 70 existing GIA models from Braun et al. (2008) with varied input parameters (rheology and ice loading history) as well as additional simulations using the SEa Level EquatioN solver (SELEN) program as described by Spada and Stocchi (2007) and Spada et al (2012) are analysed. The suite of models is

reduced by applying different ice loading histories and rheological parameters which are specifically more suitable for the Grand Banks region. Geodetic observations from GNSS stations, tide gauges and satellite altimetry are obtained and combined to estimate present day vertical crustal motion rates, which in turn can be compared with GIA predictions (Braun et al, 2008). The best fit combination of GIA model and vertical motion observation provides an estimate of approximately 1 mm/year for differential vertical motion across the Grand Banks (with some variation), and finally estimates are made to quantify the differential uplift across individual basins. This can be correlated with signatures of present-day geophysical datasets to determine the likelihood of GIA contributing to potential hydrocarbon spill among subsurface reservoirs. Additionally, acquisition of well data to identify present-day and paleo oil-water contacts is an excellent tool to assess the long-term changes in reservoir elevation, further validating model results.

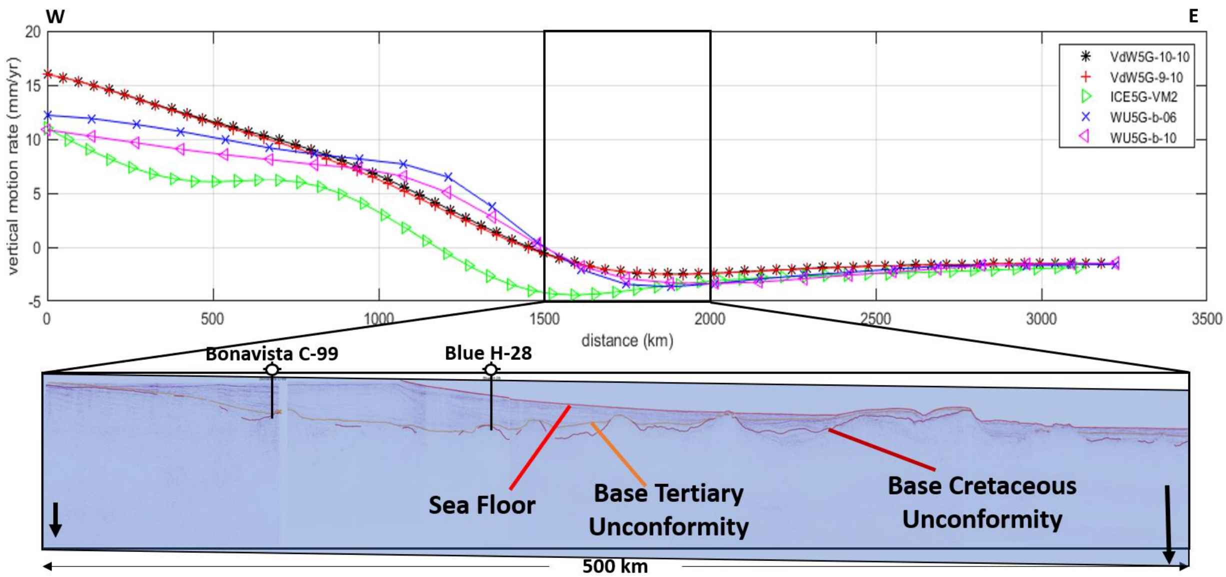

Figure 1: Conceptual representation of tilting due to glacial isostatic adjustment on basins in the Grand Banks of Newfoundland, compared to some model predictions of present-day vertical crustal motion rates. GIA models by van der Wal, Wu and Peltier (Braun et al., 2008).

Discussion

Analysis of seismic, gravity and magnetic data indicate that there is a general increase in wavelength as each successive rifting episode is analyzed. Upper crust wavelengths – observable in seismic – show wavelengths ranging from approximately 20 km to more than 50 km as profiles associated with successive rifting phases are interpreted. Additionally, the later rifting phases show dominant wavelengths of approximately 200 km in length – visible in potential field data – which are associated with the much deeper Moho undulations caused by compounding extension. There are two reasons suggested to explain this occurrence:

1. Longer wavelength features in the latter phases are due to successive extension over multiple rift phases, compounding on one another.
2. As extension occurs repeatedly at oblique angles, the crust (upper competent layer) is thinned such that the deeper Moho wavelengths become dominant and the inferred competent layer thickness is that of the upper mantle (lower competent layer)

It is very likely there is some combination of these boudinage processes leading to the longer wavelength features offshore Newfoundland.

The outputs of the modelling phase indicate that SELEN is an effective tool to simulate the process of GIA in the Grand Banks region, and there is indeed differential vertical uplift across the study area. It is worth noting that SELEN does not allow laterally varying rheologies. However, the complexity of the lithosphere structure/rheology in the Grand Banks and the uncertainty of the deglaciation history are overwhelming. Therefore, this study attempts to estimate if an impact of GIA on reservoir tilting is possible at all. Once vertical motion rates through time are determined, these expressions can be summed over time to estimate total elevation change since the Last Glacial Maximum and the time periods of previous ice ages. The impact of the mechanism at both the regional and basinal scales can then be assessed by comparing total displacement quantities at various locations and baselines.

Additive Information

Boudinage has not been suggested as a driving mechanism in the formation of many of the structures located in the Grand Banks, however the geophysical and geological data indicate that this type of deformation would be a suitable explanation in this area. This hypothesis has also been documented in other passive margins throughout the Atlantic, which reinforces the possibility of Canada's eastern margin being no exception (Braun and Marquart, 2004; Faleide et al, 2008; Clerc et al, 2018). Boudinage as a driving mechanism in the Grand Banks is a novel contribution and one that fits nicely into the current story of the region's geological evolution.

GIA modelling is not a novel concept; however, a study of the impact on hydrocarbon reservoirs has not been carried out in the Grand Banks region offshore Newfoundland. Coupled with the existing hydrocarbon production in the area, the results of a simulation that demonstrate the presence of significant differential vertical crustal motion could lead to new considerations when exploring potential future plays (Whitehouse, 2018). The issue of hydrocarbon spill from structural trapping structures is not a new one in continental passive margins, as seen in examples off the coast of Norway in the Barents, North and Norwegian Seas, and in these cases, GIA has been considered as a potential mechanism for fault reactivation and subsequent tertiary migration of leaked hydrocarbons (Kjemperud and Fjeldskaar, 1992; Bjørlykke et al, 2005; Fjeldskaar and Amantov, 2015; Ostanin, 2015; Ostanin et al, 2017). It is therefore not unreasonable to suggest that the same mechanism has been at play in the eastern Canadian continental shelf over the past 21 ka since the Last Glacial Maximum during the Wisconsinan Glaciation, and particularly within the past 15 ka as the crustal response would have had some degree of lag as deglaciation progressed.

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