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New Methods for Modelling Hyperextended and Deep Water Basins: Examples from the Atlantic and Circum-Arctic

Richard C. Whittaker and Bridget E. Ady, GeoArctic Ltd.

Summary

Deformable plate reconstructions combined with thermal subsidence and flexural uplift modelling help give us a clearer understanding of the relationship between hyperextension, sedimentary basin evolution, and basin margin uplift. These new methods of evaluating hyperextended and deep water basins provide input for environment of deposition interpretations and for basin modelling.

Introduction

Although the complex history of hyperextended margins can be problematic for the explorationist, increased deep-water exploration has resulted in new research, seismic data and modelling techniques that have provided new insights into the structural evolution of these margins in both explored and under-explored regions. Over the past decade, hyperextension has become increasingly recognized as a common extensional process on continental margins worldwide (Péron-Pindivic and Manatschal, 2009; Lundin and Dore, 2011).

Hyperextended margins are those areas where the continental crust is stretched and thinned by a factor of 3 or more. Such extreme crustal stretching and thinning results in a corresponding and often unconsidered high rate of thermal subsidence that creates accommodation space into which sediments are deposited. This requires that we re-evaluate hyperextended margins in terms of its consequences on thermal subsidence, basin architecture, and flexural uplift. During extension the amount of stretching of the continental crust generally increases from the hinge line, which marks the transition from undeformed to deformed crust, to the distal parts of the margin where maximum stretching occurs. This causes a corresponding change in facies and palaeogeography across the margin, variations in subsidence and basin margin uplift, and has consequences for heat flow and hydrocarbon maturity.

Two key modelling techniques for the reevaluation of hyperextended margins will be discussed in this paper. The first is the restoration of conjugate hyperextended margins to their pre-rift configuration by quantifying the amount, timing and direction of crustal extension and hyperextension through time (Ady and Whittaker, in press). The second is the modelling of thermal subsidence and the resulting flexural uplift across the margin (e.g. Watts *et al.,* 1982).

Modeling Method

We use a *palinspastic deformable-margin* plate reconstruction modelling method (Ady and Whittaker, in press) for the Central and North Atlantic, and Circum-Arctic (Fig. 1). This includes emerging deep-water provinces such as the Labrador Sea, Porcupine, Rockall and Orphan Basins, the Baltimore Canyon, and the southwest Barents Shelf, the circum-Arctic basins and exciting new areas such as Guyana/Suriname-Mauritania/Senegal conjugate margins.

Palinspastic deformable-margin plate kinematic models are independent of any one model for rifted margin formation and quantitatively restore the history of crustal deformation and multiple episodes of rifting or compression using geological and geophysical constraints. Unlike rigid plate models and deformable plate models that restore only the continent ocean boundaries (COB), palinspastic deformable-margin models accommodate margin asymmetry, allow for heterogeneous plane strain and are used to produce palinspastically restored pre- rift or pre-collision geometry for continent boundaries, intra-plate basins, and other tectonic features.

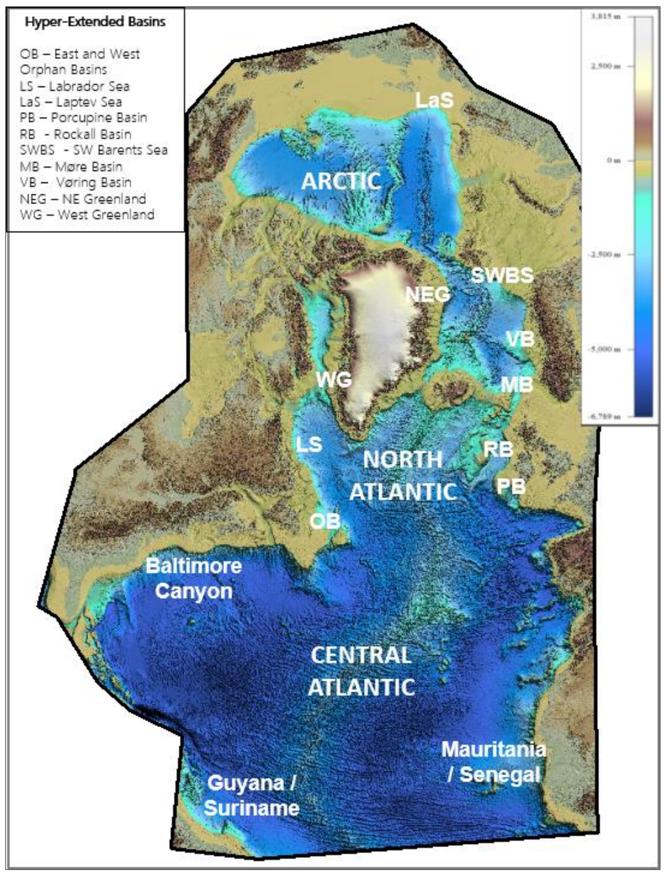

Figure 1: Key hyperextended and deep water basins and continental margins in the Central and North Atlantic, and circum-Arctic region.

The creation of large amounts of accommodation space in hyperextended basins and the rate of subsidence strongly influences the development of these basins and their margins. As the lithosphere has an inherent strength and rigidity, load changes due to extension, thermal contraction, and sediment load are not compensated locally, but are spread regionally. The extent to which loads are spread is determined by the flexural properties of the lithosphere and can be modelled (e.g. Watts *et al.*, 1982; Weissel and Karner. 1989; Kusznir *et al.*, 1991). Flexural uplift (or flexural isostasy) exerts an important regional control on sequence thickness, fault geometry, uplift and erosion in hyperextended basins.

Examples from Circum-Arctic and Atlantic Hyperextended Basins

The palinspastic deformable-margin plate model for the Central and North Atlantic, and Circum-Arctic quantitatively restores up to 350 km of Mesozoic-Cenozoic extension in some areas. The evolution and depositional history of the emerging deep-water provinces, including the Labrador Sea, Porcupine, Rockall and Orphan Basins, the Baltimore Canyon, and the southwest Barents Shelf, are discussed in light of what we now know about hyperextended margins. Each of these hyperextended margins are characterized by flexural uplift along the basin margins, resulting in features such as perched basins, and significant uplift and erosion. The ability to quantify and restore the history of crustal extension across these margins using palinspastic deformable-margin plate reconstructions provides us with restored structural profiles and backstripped 3D structural models. It also provides us with pre-rift restorations of the Proterozoic and Palaeozoic terranes and structural lineaments on conjugate margins that helps us analyse their relationship to the evolving rift axes and global plate reorganization events through time. Interpretation of these modelling results has led to a clearer understanding of the relationship between inherited structural features and their control on the rifting and breakup history.

Restoring the hyperextended basins of the North Atlantic and Labrador Sea and Baffin Bay is an essential precursor to development of a plate model for the circum-Arctic. The new palinspastic deformable-margin plate kinematic model for the circum-Arctic, constrained by gravity, magnetic and geological data, supports and further refines a three-stage opening model: 1) Early Cretaceous "windshield wiper" rotational opening of the Amerasia Basin along the Palaeozoic Ellesmerian suture, 2) mid-Cretaceous to Paleocene opening between the Amerasia Basin and the Lomonosov Ridge orthogonal to the earlier spreading direction, creating the pull-apart Podvodnikov and Makarov basins from Campanian and Maastrichtian times respectively, and 3) latest Paleocene to present day opening of the Eurasia Basin between the Lomonosov Ridge and the Barents-Kara Shelf, also orthogonal to the Amerasia Basin.

Palinspastic deformable-margin plate kinematic models quantify the timing, amount and direction of extension, compression and deformation related to strike-slip motion across a margin and are particularly important for hyperextended margins such as the Laptev Shelf, SW Barents Shelf, and NE Greenland margins. The new plate model sheds light on some of the more enigmatic features of the circum-Arctic such as the pre-rift configuration of Ellesmerian and Caledonian structural lineaments and the Northwind Ridge and Chukchi Plateau. It provides the timing and amount of extension transferred along transform zones into the Arctic from the North Atlantic along the De Geer Megashear in the Early Cretaceous and from Baffin Bay–Labrador Sea in the Late Cretaceous along the Wegener Fault Zone, charting a propagating system of seafloor spreading, hyperextension, rifting, transform and extension from the North Atlantic and Labrador Sea to the Arctic. We use the model to restore basin palaeogeometry through time and to analyse the evolution of the Palaeozoic to Cenozoic circum-Arctic sedimentary basins, including marine connectivity, basin margin (flexural) uplift, palaeogeography and the influence of structural inheritance.

Conclusions

Palinspastic deformable-margin plate reconstructions combined with thermal subsidence and flexural uplift modelling help give us a clearer understanding of the relationship between hyperextension, sedimentary basin evolution, and basin margin uplift. Hyperextended margins can easily be misinterpreted, but when the structural processes are fully understood they can provide us with potential new petroleum plays. A schematic cross-section across a hyperextended continental margin (Fig. 2) shows some examples of the types of hydrocarbon plays associated with this type of structural setting.

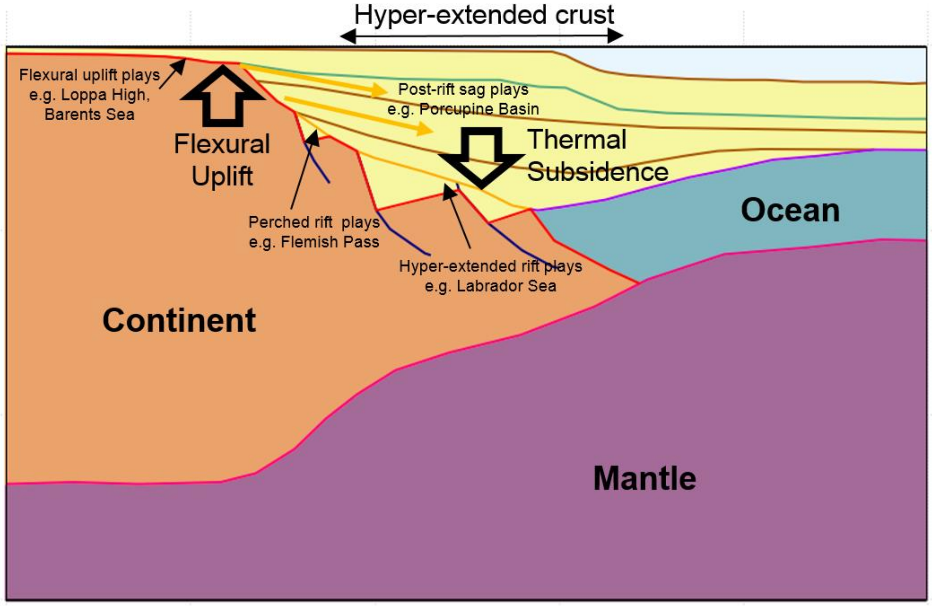

Figure 2: Schematic cross section of a hyperextended margin showing some examples of play types associated with this structural setting.

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