Introduction

As petroleum exploration becomes more focused on deep-water continental margins, plate tectonic reconstructions are increasingly important as an exploration tool. A new kinematic plate model for the North Atlantic between Ireland and Canada (Ady et al, 2010) employs a new deformable plate reconstruction method that eliminates many of the inherent short-comings found in rigid plate reconstructions, particularly the problem of plate overlap. Plate overlap is a consequence of extension, yet it can obfuscate the geological relationships critical for basin analysis in deep-water basins (Figure 1a). This paper describes a method that allows us to accurately remove the effects of pre-breakup extension across conjugate margins thereby providing a means to better evaluate basin formation and evolution. The new method takes into account the wide range of geological processes responsible for basin development by incorporating seismic, magnetic and geological interpretation with analytical techniques that include 2D or 3D gravity inversion, flexural backstripping, and forward modelling.

The plate kinematics of the North Atlantic Ocean has been well documented and there is general agreement that extensional deformation started in Triassic times and lasted until the Tertiary, with final separation between the Flemish Cap and Galicia Bank occurring in the Early Cretaceous and between Greenland and the Hatton Bank in the Tertiary. However, there are also several key areas of speculation that include, for example, the role of the Orphan Basin in the overall evolution of the North Atlantic. The effect of large amounts of extension in the Orphan Basin on the relative movement of the Flemish Cap during the Cretaceous is presented here as a striking example of how geologically constrained deformable plate techniques that incorporate kinematic and dynamic modelling can provide insight that is not available through traditional rigid plate reconstruction methods.

Methods

The deformable plate reconstruction method presented in this paper advances earlier ideas first put forward by Srivastava and Verhoef (1992) for the removal of extension at plate margins. Their approach, however, used a gross estimation of continental lithosphere extension (β factors) from the measurement of plate overlap, which cannot account for lateral, depth-dependent, and time-dependent variations in the amount and direction of extension or movement in the vertical plane due to tectonic subsidence. Whittaker et al (2000) first describe a 4D deformable plate reconstruction using β factors calculated from 3D tectonic subsidence maps as input. This method has further evolved to include the wide range of geological processes responsible for basin development as input into a deformable plate model. The deformable model comprising calculations of vertical movement and lateral, depth-dependent, and time-dependent variations in the amount and direction of stretching are stored as TINs (*Triangulated Irregular Networks)*, a vector data structure that partitions geographic space into contiguous, non-overlapping *Delaunay* triangles. Using proprietary in-house tools, the information stored in the TINs can be applied to any gridded or vector datasets such as structure maps, palaeogeographic maps, wells, license blocks, and seismic lines, etc. to restore their original geometry at any given time.

As a starting point for model input, gravity inversion using globally available free-air gravity, bathymetry and sediment thickness data has been used to determine crustal thickness, residual continental crustal thickness, Moho depth, and continental lithosphere extension factor. The inversion method used in this study incorporates a lithosphere thermal gravity anomaly correction and a volcanic addition correction to encompass all margin types within the study area (Alvey et al, 2008). This method provides a gross extension factor for the whole crust and is particularly useful in areas where seismic refraction data is sparse or non-existent. The results have been compared to seismic refraction data, where available, and integrated with detailed local studies around the margin (e.g. Welford et al, 2010).

A regional seismic grid has been interpreted on each conjugate margin using a combination of high quality deep long-offset industry data, and reflection and refraction seismic profiles from government and academia. Key regional seismic profiles were selected on the conjugate margins for 2D flexural backstripping to establish the timing and amount of pre-breakup extension that has occurred. Selected seismic lines include deep long-offset seismic data on the Irish margin (courtesy of ION-GX Technology) and the Orphan Basin (courtesy TGS-Nopec). Major tectonostratigraphic sequences defined from seismic interpretations around the margin are mapped to produce isopachs that are used to provide an estimate of the 3D tectonic subsidence for each time interval. If depth-dependent stretching has occurred, it would result in upper-crustal extension that does not balance estimates of deeper stretching and thinning, in which case the β factor from gravity inversion is a maximum estimate of upper crust extension. It is also important therefore to calculate the fault-controlled extension in the upper crust either by modelling tectonic subsidence or flexural backstripping. The results of the gravity inversion studies, flexural backstripping along selected regional profiles and tectonic subsidence calculations are used to determine crustal extension for each time interval for the deformable model.

The final step is to apply the deformable model to restore palaeogeography and other maps to their original geometry at any point in time and then reconstruct them to their palaeo-position at that time for use in basin analysis. These restored and reconstructed maps can be used to determine palaeobathymetry, palaeoenvironment, source rock and reservoir facies, etc. The entire modelling process is iterative and is carried out until a good fit for model predictions and geological constraints are found, often resulting in further refinement to published poles of rotations describing relative plate motion, particularly in the pre-breakup phase.

Example

The application of the new deformable plate reconstruction methods provides an insight into the development of the southern North Atlantic margin in the area of the Flemish Cap and Galicia Bank. Reconstruction of the conjugate margins using rigid plate reconstruction techniques results in considerable overlap (Figure 1a). However there is no evidence of significant extension of the Flemish Cap indicating that it is an intact block of continental lithosphere and for the sake of simplicity, it has been previously described as acting with the behavior of a microplate (Srivastava et al, 2000; Sibuet et al, 2007). The microplate analogy is used in order to describe the motion of the Flemish Cap relative to the North American plate with the Flemish Cap requiring a separate pole of rotation to describe its relative plate motion. There is no evidence for a plate boundary between the two plates, nor is it regarded as a major strike slip boundary, consequently the use of "microplate" as an analogy is misleading.

Our work shows that the apparent rotation of the Flemish Cap can be explained quite simply by the differential extension in the surrounding area during the Cretaceous. Gravity inversion results indicate that the cumulative extension in the East and West Orphan Basins to the northwest of the Flemish Cap is much higher than the area to the west of the Flemish Cap, which includes the Jeanne d'Arc and Flemish Pass basins (Figure 1b). The application of deformable plate reconstruction techniques to remove the differential extension results in the clockwise rotation of the intact continental lithosphere of the Flemish Cap relative to North America with a vector of movement corresponding to that described by Sibuet et al (2007) from their examination of the geological and geophysical constraints (Figure 1b). The example from the Flemish Cap demonstrates the advantages of the deformable plate method in basin analysis. While it confirms the clockwise rotation of the Flemish Cap relative to North America, it demonstrates that the mechanism driving this movement can be quite simply explained by differential intra-plate extension, thus eliminating the problematic analogy of inter-plate ("microplate") movement requiring a separate pole of rotation for the Flemish Cap.

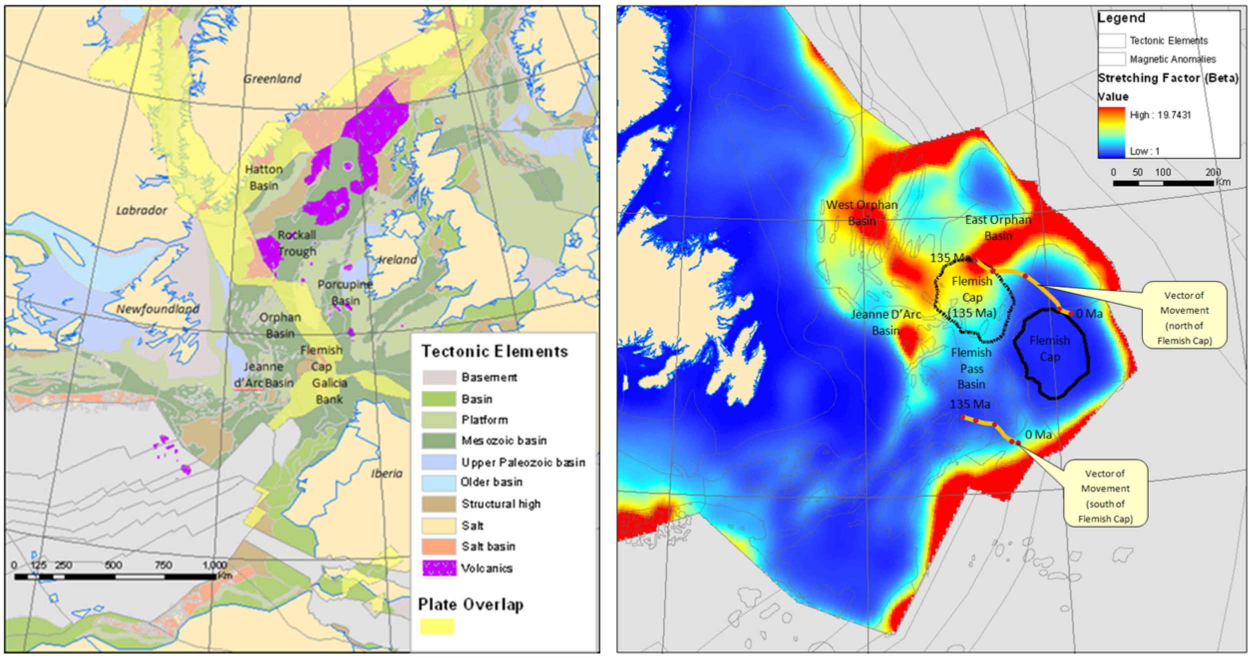

Figure 1 a) *Rigid plate reconstruction of the study area at 135 Ma (Hauterivian) showing plate overlap, and major tectonic elements (Eurasia fixed plate);* ***b)*** *Rotation and movement of the undeformed Flemish Cap as a result of differential extension. Beta values show considerably greater cumulative extension in the Orphan Basin than in the Flemish Pass Basin to the south and west.*

Conclusions

The new deformable plate reconstruction method benefits from advances in the fields of kinematic and geodynamic modelling, while making use of all available onshore and offshore geological constraints. The ability to apply the results of deformable plate modelling to data that is vital for oil and gas exploration in order to restore their pre-breakup geometry represents a major advance over the rigid plate models. Restored structure maps, palaeogeography maps, sediment source area maps, source rock and reservoir facies maps may be reconstructed to their palaeo-position to be used to evaluate source rock and reservoir potential. Application of these methods will give us an enhanced understanding of the major controls and mechanisms for basin formation and evolution in offshore Atlantic Ireland and Eastern Canada, which has implications for basin analysis and petroleum exploration in those areas.

Acknowledgements

The authors would also like to thank Badley Geoscience Ltd for gravity inversion work and Kim Welford, Memorial University of Newfoundland, for providing her regional gravity inversion results.

This publication uses data and survey results acquired during a joint project funded by the Irish Shelf Petroleum Studies Group (ISPSG) and Nalcor Energy (on behalf of the Offshore Geoscience Data Program with the Government of Newfoundland and Labrador). The ISPSG comprises: Chevron Upstream Europe, ENI Ireland BV, ExxonMobil International Ltd, Hess Exploration Ireland Ltd, OMV (UK) Ltd, Providence Resources plc, San Leon Energy Plc, Serica Energy Plc, Shell E&P Ireland Ltd, Sosina Exploration Ltd, Statoil Exploration (Ireland) Ltd and the Petroleum Affairs Division of the Department of Communications, Energy and Natural Resources.

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