3D Modeling the Gaspé Belt basin deformation: palinspastic restoration, kinematics and HC fluid flow

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Summary

The building of a 3D structural model is a necessary step in basin analysis for hydrocarbon exploration. We highlight the essential role of the restoration in calibrating the Gaspé Belt basin model. The building of a surfacic 3D model at present time coupled with the restoration step allows to reconstruct the geological history of the sedimentary basin.

Working in three-dimensional allowed to verify the truthfulness of different geological interpretations, to identify the presence of three new faults, and to better locate Bras-Nord-Ouest and Troisième Lac faults. The restoration allowed to study the coherency of the model and improve the interpretation of the faults kinematics.

Introduction

Since 150 years, the Gaspé Peninsula is recognized for its oil potential and recent discoveries of oil have led to a sustained exploration activity. During the 1990s, geological field studies have been focus on understanding the structural and stratigraphic architecture of the Silurian-Devonian Gaspé Belt basin and geochemical studies have helped to identify the main source rocks. Reprocessing of seismic lines in the public domain with modern softwares enables to obtain new images of the basin structure at depth. A new 3D approach is considered in this study to unravel the complex geometry of the Gaspé Belt basin with the perspective to better understand its petroleum system. The study area is in the northeastern part of the peninsula (Fig. 1) where the largest number of oil indices (oil seeps, sounding, etc.), seismic lines and geochemical data are found.

In a first step, a 3D surfacic structural model of the region is constructed with seismic lines migrated in depth using the velocity model of Bêche et al. (2007). The building of the 3D model is then improved by surface restoration. This paper presents this first step of the study. In the second step for understanding the petroleum system in the Gaspé Belt basin, basin modelling software will be used for simulating the generation and migration of hydrocarbons.

Structural style

The Gaspé Belt forms a broad regional depositional belt in the Canadian Appalachians which is made of Upper Ordovician to Middle Devonian rocks. They rest unconformably on Cambrian-Ordovician rocks in the northern Gaspé Peninsula, whereas they are unconformably overlain by Carboniferous rocks in the southern part of the peninsula (Fig. 1). Silurian-Devonian rocks of the Gaspé Belt were mainly deformed by the middle Devonian Acadian orogeny. They are affected by NE-trending, open and upright folds (Fig. 1). NE-trending and NW-verging reverse faults are common in the northern part of the basin. In the southern part of the basin, major faults are E-trending dextral strike-slip faults. In the northeastern part (our study area measuring 45000m E-W and 34000m N-S; Fig. 1), major faults are NW-trending; they played as syn-sedimentary normal faults during Late Silurian-Early Devonian and as dextral oblique-slip faults during the

Acadian deformation. Folds, reverse faults and strike-slip faults in the southern part are compatible with a model of dextral transpressional deformation related to the Acadian orogeny (Malo and Kirkwood, 1995). New seismic reflection data in the northern part of the basin reveals a geometry with structures typical of folds and thrust belt (NW-verging blind thrusts, SE-verging backthrust, triangle zones, and duplex) in the Silurian-Devonian rocks (Kirkwood *et al.* 2004). These structures have preceded the late major strike slip faulting.

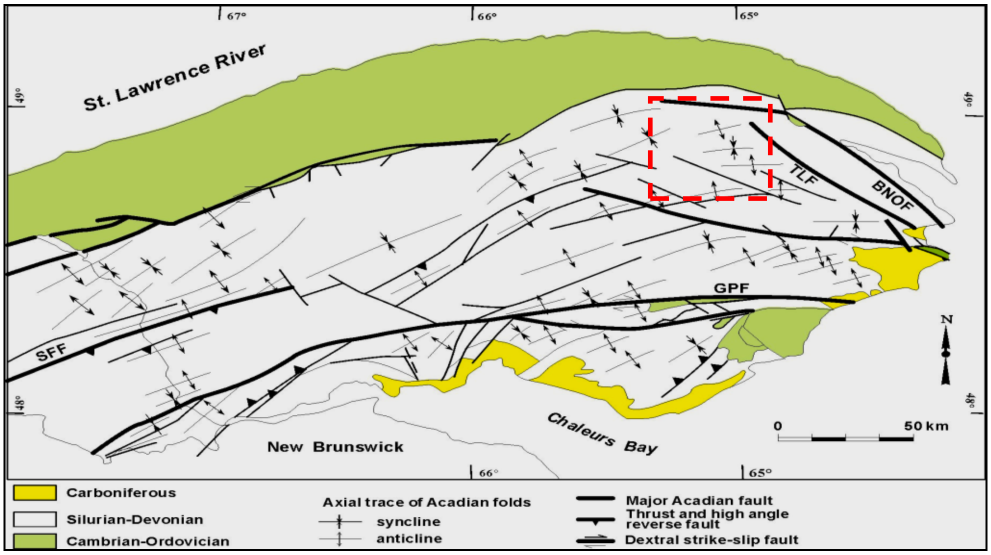

Figure 1: Simplified geological map of the Gaspé Peninsula. SFF - Sainte-Florence fault (ex. NW-verging reverse fault – northern part), GPF – Grand Pabos fault (ex. E-trending dextral strike-slip fault – southern part), TLF – Troisième Lac fault and BNOF – Bras Nord-Ouest fault (ex. dextral oblique-slip faults – northeastern part). The red dotted square represents the study area (Malo *et al*. 2009).

Structural modeling of the area of interest at present day

3D geological modeling represents an interesting approach to visualize, understand and analyze a structural environment, especially when they suffered successive stages of deformation.

In Earth Sciences, the building of 3D structural surfacic models is widespread, as a first step for the integration and interpretation of data (seismic lines, etc). This step is necessary especially if the available data are heterogeneous. The building of valid and coherent 3D model needs numerous iterative steps in order to improve the quality of the interpretation. Before getting a complete three-dimensional model for a petroleum system evaluation, the second step is to construct the structural section at present time to ensure consistency of the geological interpretation (Galera *et al.* 2003). A surfacic model is established using the Gocad software from seismic reflexion data, geological map, structural cross-sections and field measurements.

Working in three-dimensional with 2D seismic data allowed to verify the truthfulness of different geological interpretations made in recent years. Furthermore, we could identify the presence of three new faults (named Fault 1, Fault 3A and 3B) near the BNOF already listed (Fig. 1). The addition of geophysical data (for example: second vertical derivative or shaded relief image of the residual total magnetic field data...; Pinet *et al.* 2005) enables us to add information in our initial model, which confirms the presence of new faults and adjusts the old ones. For example: we have located the exact position of the BNOF using aeromagnetic data (Fig. 2).

Another example, correlated with the restoration, the NW-trending Acadian faults in the northeastern Gaspé are dextral strike slip (TLF and BNOF; Fig. 1). The strike-slip motion along these faults represents the latest Acadian movement (Malo and Kirkwood, 1995). In our study, we confirm the strike-slip motion along the TLF, but not along the BNOF in its northern segment.

The BNOF records a pre-Silurian ductile strike-slip motion attributed to the Taconian orogeny and synsedimentary normal movements during Late Silurian to Early Devonian time (Malo and Kirkwood, 1995). This normal faulting was inverted in post-Middle Devonian time by the Acadian transpression (mainly strike-slip with high-angle reverse motion in its southern segment and most likely thrust/reverse faulting in its northern segment in our study area; Fig.1).

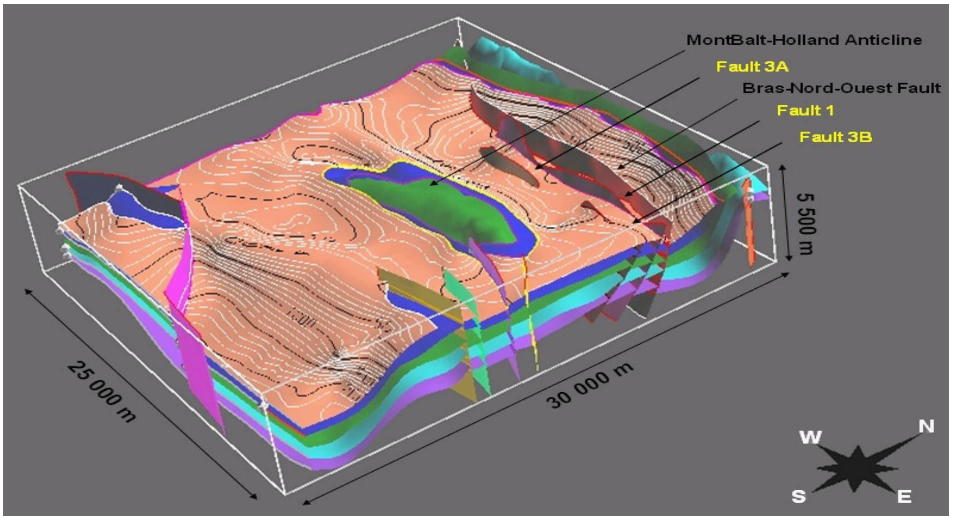

Figure 2: Sectional view of the Gocad surfacic model of the study area in northeastern Gaspé Peninsula with erosion (Eastside view). The first orange surface is the Shiphead Formation, the second blue is the Forillon Formation, the third green is the Chaleurs Group (Saint–Léon Formation), the last two surfaces are unnamed reflectors. Subvertical surfaces are faults identified in the study area. The yellow names are the names of newly identified faults.

Structural evolution through time

As we have seen above, when working in complex areas, one needs to construct 3D models for checking their coherency with existing data. Coherence can be analyzed on the current geometry but could also be quantified through restoration, a method to quantify the deformation between the present day and the deposition time (Gibbs, 1983). It helps in improving the interpretation of the kinematics of the faults, in better understanding the structures from a dynamic point of view, so to ensure the coherency of the model constructed. We use an iterative system:

Seismic interpretation ←→Building surfacic model ←→Restoration.

As geology of northeastern Gaspé Peninsula is still subject to issues (such as the set of fault displacements), the restoration (Fig. 3) has helped us better understand the faults, like the Bras-Nord-Ouest fault (Fig. 1), by testing their coherency.

In Figure 3, we can see the Shiphead Formation at present time versus the Shiphead Formation at deposition time. Both surfaces have kept the same area (about 1,55.10^9 m2). We observe on the surface restored an increase of 3,8% in N-S, while we see no decrease in E-W. The accommodation was therefore carried out by the North-South shortening of the system and the shortening direction confirms the movement of the BNOF.

Conclusions

In conclusion, exploration in complex areas is more risky; it is critical to know not only the restored state before deformation (consistency of interpretations) but also to reconstruct the kinematics of deformation. Thus, the reconstruction provides a 3D-paleogeographic model, allowing us to better assess the chronology of geological events. This structural building is the first phase of the project prior to the assessment of petroleum system in the Gaspé Peninsula (Malo *et al.* 2009).

A: **B:**

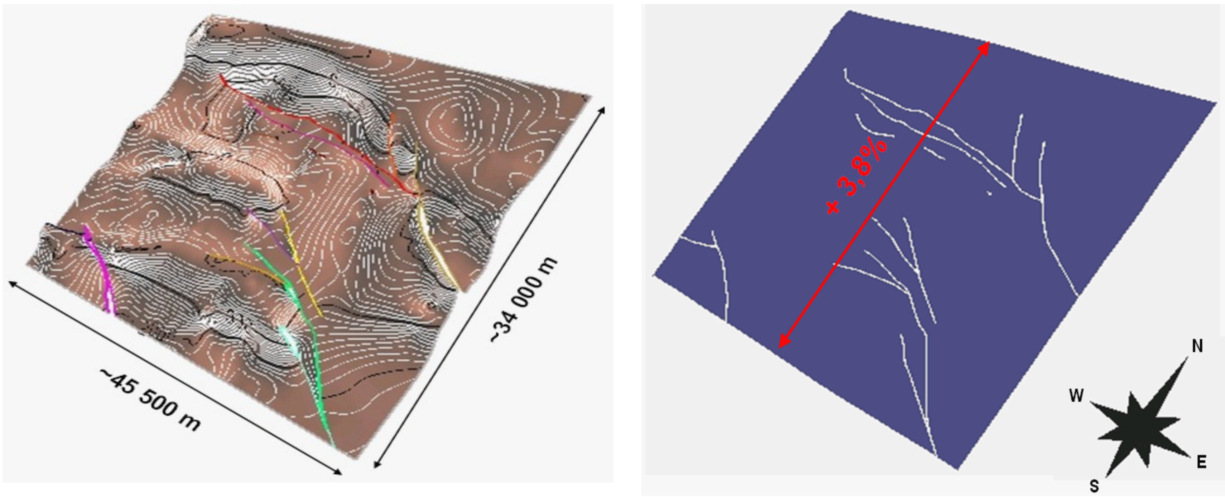

Figure 3: Comparison of deformed surface at present time (Fig. 3 A) with the restored surface at deposition time (Fig. 3 B), on the complete block. A: Topographic map with white contour lines every 500m and black contour lines every 1000m. Colours lines (yellow, green, red..) are faults traces in the surface. B: The restored surface is a plane surface and white traces are fault traces.

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