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Geometric and Kinematic Reconstruction of the Chaleurs Bay Synclinorium (Gaspé Belt) through the Integration of Geological and Geophysical Data

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Summary

The integration of 2D seismic interpretation, gravity modeling, and thermal maturity data reveals the superposition of four different deformation styles, developed over four deformation phases in the Chaleurs Bay area, Quebec, Canada. The first deformation phase (Tremadocian-Arenigian; Taconic Orogeny) is characterized by a southeast-directed hinterland dipping duplex mostly involving the Hadrynian-Lower Cambrian Maquereau Group. The second deformation phase (Late Ordovician; post-Taconic extension) is marked by the development of a ramp-flat listric extensional fault system which controlled the deposition of the Upper Ordovician Honorat and Matapédia Groups. During the third deformation phase (Middle Devonian; early stage of the Acadian Orogeny) thrusts faults inherited from the Taconic Orogeny are reactivated and normal faults inherited from the post-Taconic extensional phase are inverted. Strike-slip faulting along the Grand-Pabos and Garin River faults occurred during the fourth deformation phase (Middle/Late Devonian; late stage of the Acadian Orogeny). Tectonic transport towards the southeast documented in this study suggests that the Taconic orogen in the Gaspé Peninsula is a doubly-vergent orogen.

Introduction

The Chaleurs Bay Synclinorium contains an assemblage of regional NE-SW-trending folds and major E-W and NE-SW-trending faults, mostly involving rocks of the Upper Ordovician Matapedia Group and the Silurian Chaleurs Group (Bourque *et al.*, 1993) **(fig. 1)**. These dominant structural features have been attributed to the Acadian Orogeny (De Broucker, 1987; Malo and Béland, 1989; Malo and Bourque, 1993; Kirkwood and Malo, 1993; Malo and Kirkwood, 1995; Malo *et al.*, 1995; Malo, 2001). However, the knowledge of the subsurface geology of the Chaleurs Bay Synclinorium and the Aroostook-Percé Anticlinorium of the Gaspé Belt is still limited due to the poor quality of seismic reflection data and few deep wells. A regional 2D seismic reflection data acquisition program of about 470 km was conducted by the Ministry of Natural Resources of Quebec in the Gaspé Peninsula between 2000 and 2003. Most of these data have already been studied and interpreted (Kirkwood *et al.*, 2004; Bêche *et al.*, 2007; Pinet, 2013) with the exception of two seismic lines acquired on the Aroostook-Percé Anticlinorium and the Chaleurs Bay Synclinorium. The purpose of this study was to obtain a structural interpretation along seismic lines 2001-MNR-14A and 2001-MNR-14B **(fig. 1)**, with a total length of 59 km, acquired north of Bonaventure (Quebec), in order to characterize the structural style of the post-Taconic successor basin and to reconstruct the history of the deformation of the Chaleurs Bay Synclinorium.

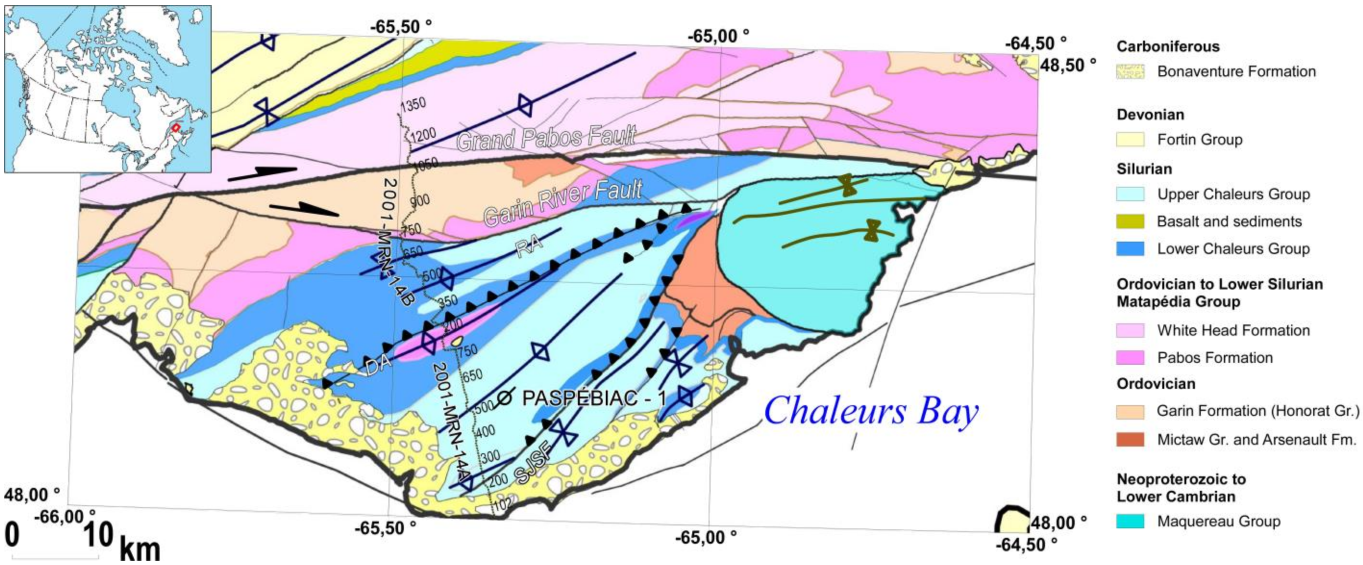

Figure 1. Geologic map showing location of seismic lines 2001-MRN-14A and 2001-MRN-14B and well Paspébiac-1, north of Chaleurs Bay. DA: Duval Anticline; RA: Robidoux Anticline; SJSF: Saint-Jogues Sud Fault (modified from: Pinet, 2013).

Method

The seismic interpretation was constrained by the geological map (Lachambre and Brisebois, 1990) and formation tops penetrated by well Paspébiac No. 1 (Junex, 2008). The seismic interpretation was converted into depth by using interval velocities derived from velocity analysis of prestack seismic data so it could be used as a constraint for the gravity modeling. An anomaly profile was extracted from the Bouguer anomaly map (Pinet *et al.*, 2005) and was later decomposed into a regional and a residual component by the visual adjustment method (Pinet *et al.*, 2006). The gravity model was constrained by measured densities of the units (Pinet *et al.*, 2005). Through an iterative process, the results of the gravity modeling were used to modify the seismic interpretation and this new seismic interpretation was used to build a new geological model. The cross-section resulting from surface data analysis, seismic interpretation and gravity modeling was compared with published analog models in order to better understand the geometry and kinematic implications.

2D Seismic Reflection

In our interpretation, the faults that cut across the Silurian rocks at the surface also affect the underlying Cambrian-Lower Ordovician rocks. As for the Grand Pabos and the Garin River strike-slip faults, the interpretation suggests subvertical dips, with a connection of both faults at depth. Low amplitude, short wavelength folds and reverse faults with a small throw involving **Cambro-Ordovician (sub-Taconic unconformity) units** have been interpreted as a system of partially inverted normal listric faults (Gibbs, 1984). Reflections of the Upper Ordovician Garin Formation (Honorat Group) onlapping mimic the syn-rift units onlap at the crest of the roll-over anticline, illustrated by scaled analog models of ramp-flat listric extensional fault systems (McClay, 1995). Divergent reflections attributed to syn-rift units of the Matapedia Group, south of the Garin River Fault, are compatible with an episode of post-Taconic extension. Based on the comparison to a scaled analog model, major Acadian folds of the Chaleurs Bay Synclinorium are interpreted as the result of tectonic inversion of a post-Taconic upper crestal collapse graben (McClay, 1995).

Gravity

In the model, the positive (southern) anomaly is reproduced mainly through tectonic stacking of Cambrian-Ordovician units, including the high-density greenschist facies Maquereau Group. The negative anomaly is reproduced mostly by the total absence of the Maquereau Group and infilling by the relatively low-density Upper Ordovician Pabos Formation of the Matapedia Group. The calculated residual gravity anomaly curve, computed from the density distribution derived from the geological interpretation, nicely mimics the observed anomaly curve. The gravity modeling suggests: (1) the position of the Proterozoic basement at a depth of about 10 km, (2) the presence of a tectonic stacking of Cambrian-Ordovician units, as suggested by the seismic interpretation, and (3) the presence of a thick succession of relatively low-density syn-rift **sedimentary rocks** (Pabos Formation) deposited **during** a post-Taconic extension episode.

Correlations with existing thermal maturity data

Most of outcropping rock units are in the condensate to dry gas windows and exhibit a constant decrease in the average estimated vitrinite equivalent-reflectance values from the base to the top of the stratigraphic column. A notable exception corresponds to the Mictaw Group – at the base of the stratigraphic succession which is still in the oil-window (Roy, 2008). This indicates that the Mictaw Group – in the southeast sector of the Chaleurs Bay Synclinorium – experienced a completely different burial history than the rest of the succession – in the northwest sector. This contrasting history is compatible with the development of a major unmapped post-Taconic listric extensional fault, located between the Mictaw Group (Port-Daniel area) and the Matapédia Group (Duval Anticline). According to our model, rocks of the Mictaw Group in the footwall – southeast of this major fault – were preserved from significant post-Taconic burial, while syn-extension strata were deposited during the post-Taconic extension phase, northwest of this fault.

Discussion

Kinematics and timing of deformation

The subsurface geometry obtained from the integration of geological data, 2D seismic reflection data, gravity modeling, thermal maturity data, and the comparison to a scaled analog model allows us to postulate schematically the structural evolution of the Chaleurs Bay Synclinorium **(fig. 2)**:

(1) Tremadocian-Arenigian. The Taconic orogen, below the Chaleurs Bay Synclinorium, is characterized by a SE-directed hinterland dipping duplex involving the Maquereau Group **(fig. 2a)**.

(2) Darriwillian-Caradocian. Time correlative Arsenault Formation and Mictaw Group are deposited during a relatively quiescent interval **(fig. 2b)**.

(3) Caradocian-Rhuddanian. The post-Taconic extension is characterized by the deposition of the Honorat and Matapedia Groups during the development of a ramp-flat listric extensional fault system (Gibbs, 1984) involving the Proterozoic basement **(fig. 2c)**. This deformation episode generated typical structures of such extensional systems, including a roll-over anticline, two crestal collapse grabens, and onlapping syn-rift units.

(4) Rhuddanian - Pridolian. The occurrence of a relatively quiescent period is supported by the relatively constant thickness and the absence of documented syn-sedimentary faults in the Chaleurs Group **(fig. 2d)**.

(5) Middle to Late Devonian. The Acadian Orogeny can be divided into two distinct phases: an early phase of shortening, followed by a late phase of dextral strike-slip faulting (Malo and Kirkwood, 1995). The early phase of shortening **(fig. 2e)** is represented by the development of regional NE-trending folds and associated cleavage. In our interpretation, folds are generated by reactivation of old Taconic thrusts and inversion of post-Taconic normal faults with tectonic transport to the southeast. The late dextral strike-slip faulting is represented by the Grand Pabos fault system which displaced the early Acadian regional folds, as it is seen today **(fig. 2f)**.

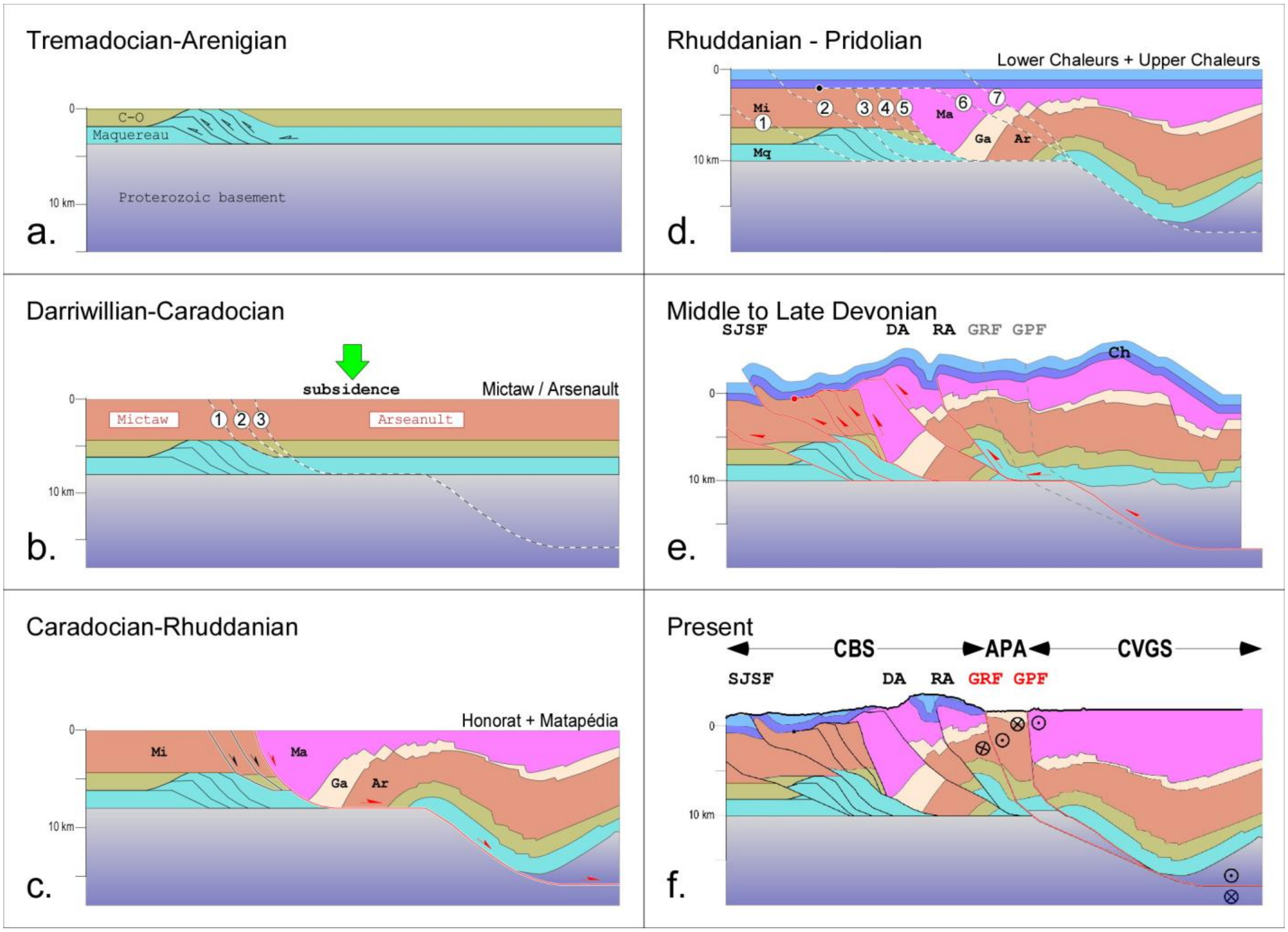

Figure 2. Structural evolution of the Chaleurs Bay Synclinorium and the Aroostook-Percé Anticlinorium. North is to the right. APA: Aroostook-Percé Anticlinorium; Ar: Arsenault Formation; CBS: Chaleurs Bay Synclinorium; Ch: Chaleurs Group; C-O: non-metamorphosed Cambro-Ordovician; CVGS: Connecticut Valley-Gaspe Synclinorium. DA: Duval Anticline; Ga: Garin Formation; GPF: Grand Pabos Fault; GRF: Garin River Fault; Mi: Mictaw Group. Mq: Maquereau Group; Mt: Matapedia Group; RA: Robidoux Anticline; SJSF: Saint-Jogues Sud Fault.

Conclusions

The integration of geological data, 2D seismic reflection, gravity modeling, and thermal maturity data from the Chaleurs Bay Synclinorium, reveals the superposition of four different deformation styles, developed over four deformation episodes. Our study lead to several new findings that bear significant implications on the geological evolution model and petroleum potential of the area : (1) the existence of Taconic thrust sheets with the southeast tectonic transport suggests that the Taconic orogen in the Gaspé Peninsula is a doubly vergent orogen; (2) major Acadian folds of the Chaleurs Bay Synclinorium are interpreted as the result of tectonic inversion of a post-Taconic *upper crestal collapse graben* (McClay, 1995); (3) the coexistence of rock units with contrasting burial histories is interpreted as the result of post-Taconian extension normal motions along a major, previously poorly documented, fault.

Acknowledgements

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