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

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1. 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, the 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, the 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, the 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, the Middle to Late Devonian **late** stage of the **Acadian Orogeny**.

The Gaspé Belt

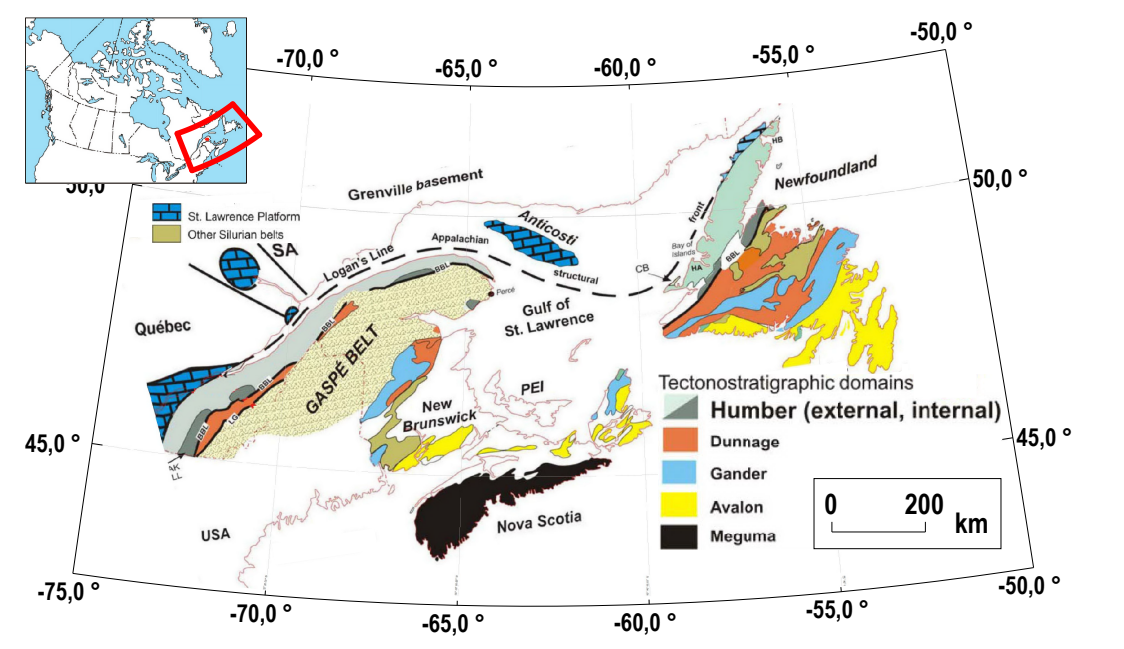


Figure 1. The Gaspé Belt and Taconic tectonostratigraphic domains of the Canadian Appalachians (modified from Lavoie, 2008). The Gaspé Belt is the largest **post-Taconic Successor Basin** of the Middle Paleozoic of Canadian Appalachians (Williams, 1995). It includes a succession of Upper Ordovician to Upper Devonian sedimentary and volcanic rocks that overlies unconformably or are in fault contact with Cambro-Ordovician units belonging to the Humber, Dunnage and Gander (Lower Paleozoic) Zones (Brisebois and Brun, 1994; Bourque *et al.*, 2001; Malo, 2001; Malo *et al.*, 2008).

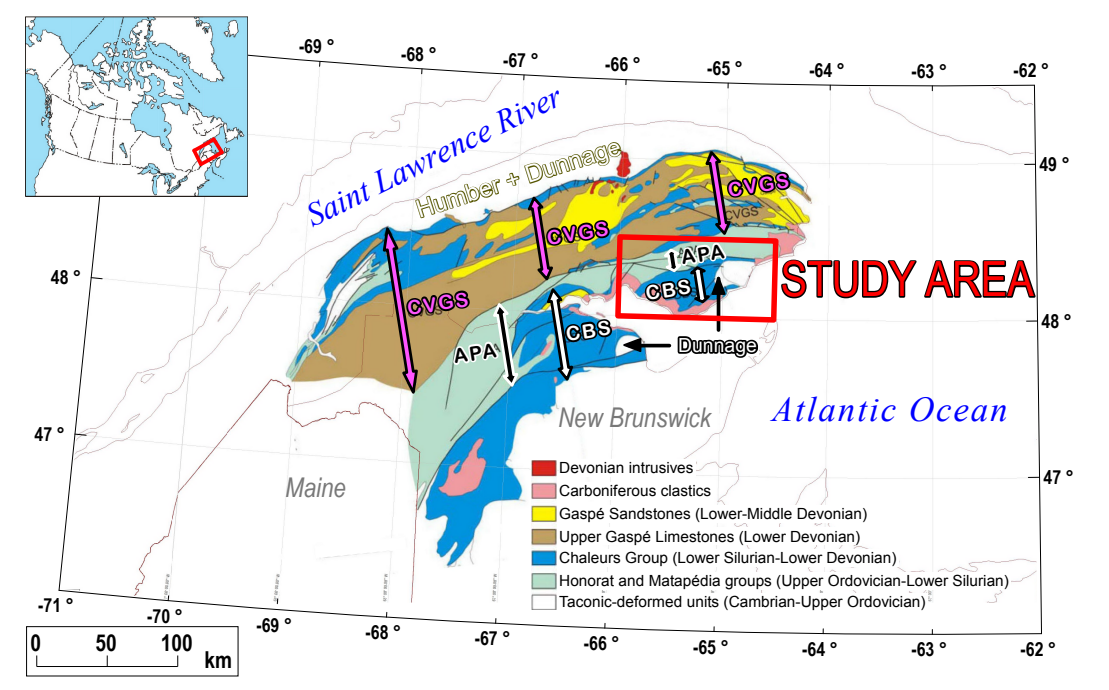


Figure 2. Main tectonostratigraphic domains of the Gaspé Belt (modified from Lavoie, 2008). The Gaspé Belt has been subdivided into three tectonostratigraphic areas, which are from north to south: (1) the Connecticut Valley-Gaspé Synclinorium (**CVGS**), (2) the Aroostook-Percé Anticlinorium (**APA**), and (3) the Chaleurs Bay Synclinorium (**CBS**) (Brisebois and Brun, 1994; Bourque *et al.*, 2001; Malo *et al.*, 2008).

2. Introduction

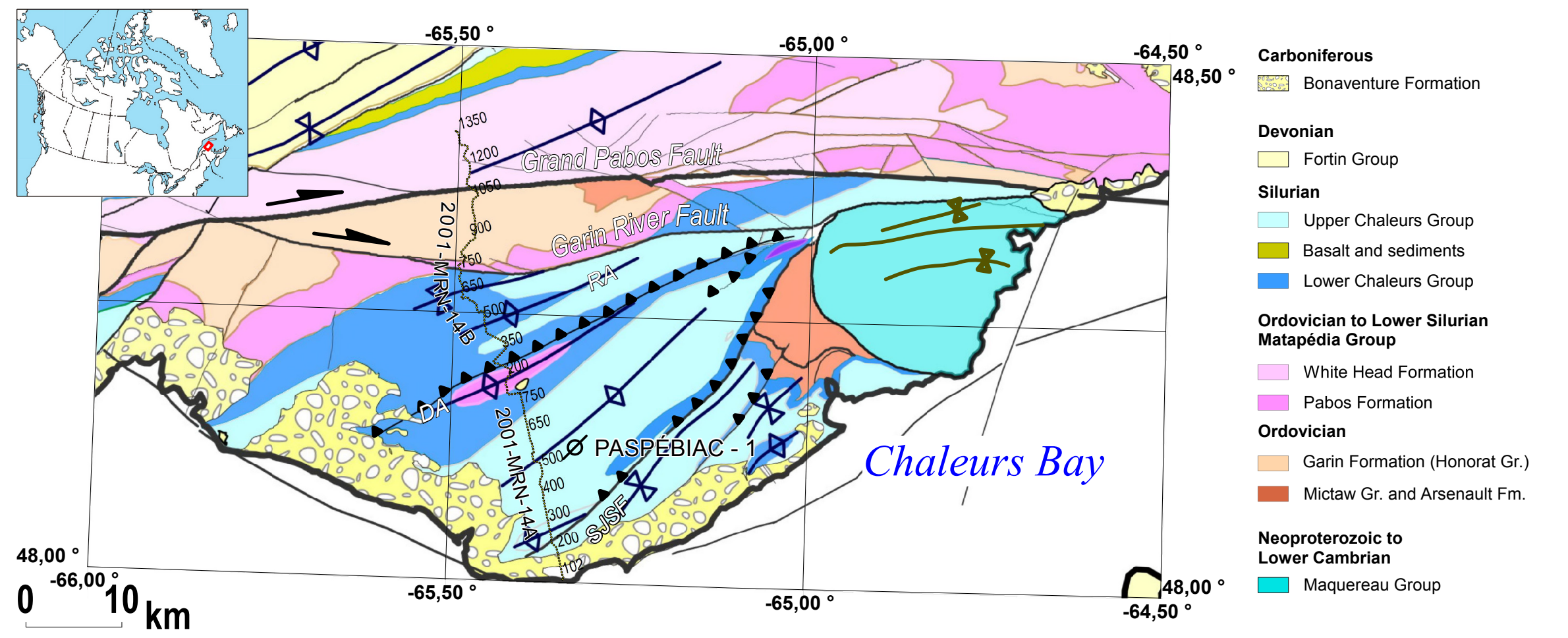
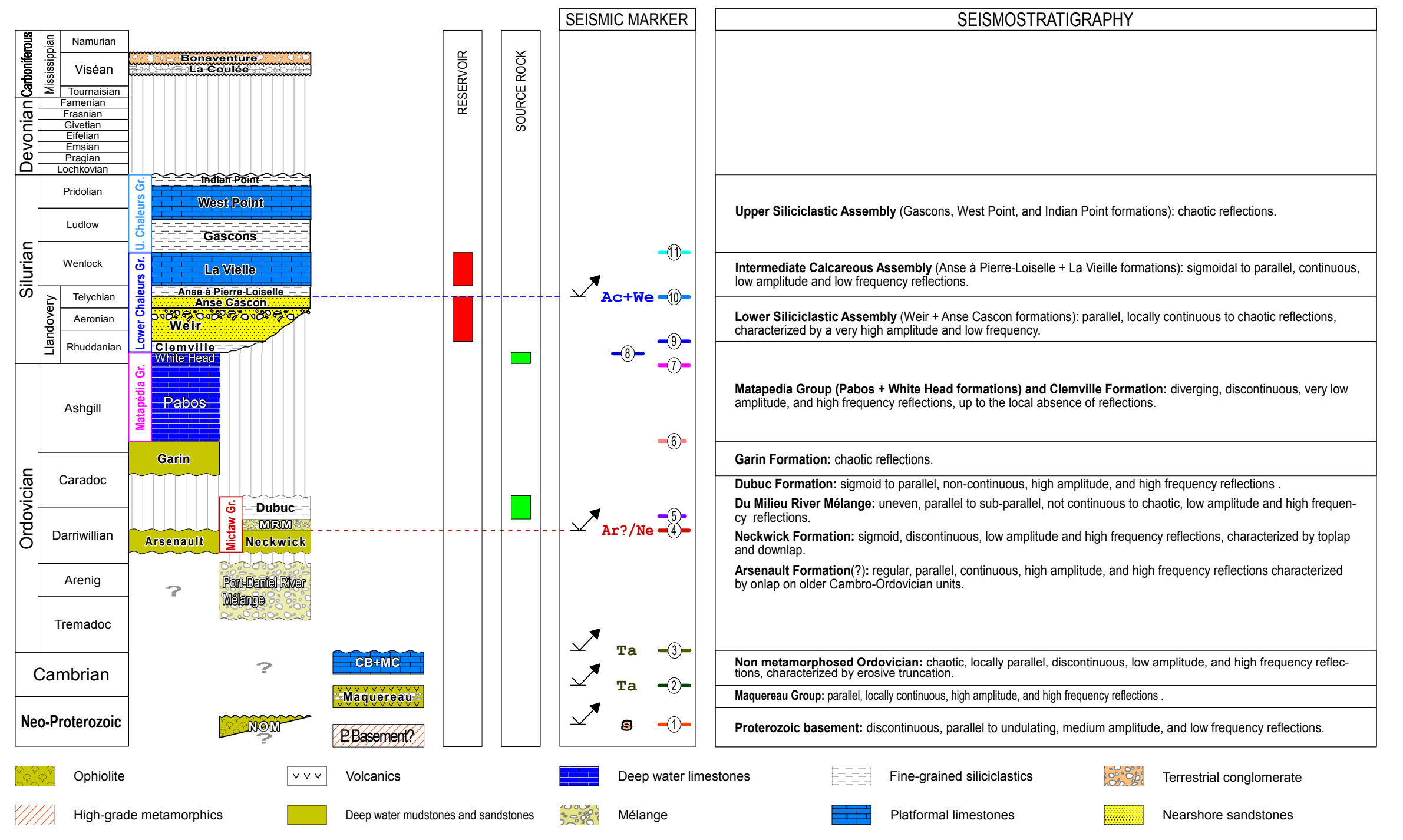


Figure 3. Geologic map showing location of seismic lines 2001-MRN-14A and 2001-MRN-14B and well Paspébiac-1, north of Chaleurs Bay. DA: Duval Anticline; RA: Robidoux Anticline; SJSF: Saint-Jogues Sud Fault (modified from: Pinet, 2013). The Chaleurs Bay Synclinorium contains an assemblage of regional 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.

Regional Stratigraphy and Seismostratigraphy



Upper Siliciclastic Assembly (Gascons, West Point, and Indian Point formations): chaotic reflections.

Intermediate Calcareous Assembly (Anse à Pierre-Loiselle + La Vieille formations): sigmoidal to parallel, continuous, low amplitude and low frequency reflections.

Lower Siliciclastic Assembly (Weir + Anse Cascon formations): parallel, locally continuous to chaotic reflections, characterized by a very high amplitude and low frequency.

Matapedia Group (Pabos + White Head formations) and Clemville Formation: diverging, discontinuous, very low amplitude, and high frequency reflections, up to the local absence of reflections.

Garin Formation: chaotic reflections.

Dubuc Formation: sigmoid to parallel, non-continuous, high amplitude, and high frequency reflections .

Du Milieu River Mélange: uneven, parallel to sub-parallel, not continuous to chaotic, low amplitude and high frequency reflections.

Neckwick Formation: sigmoid, discontinuous, low amplitude and high frequency reflections, characterized by toplap and downlap.

Arsenault Formation(?)**:** regular, parallel, continuous, high amplitude, and high frequency reflections characterized by onlap on older Cambro-Ordovician units.

Non metamorphosed Ordovician: chaotic, locally parallel, discontinuous, low amplitude, and high frequency reflections, characterized by erosive truncation.

Maquereau Group: parallel, locally continuous, high amplitude, and high frequency reflections .

Proterozoic basement: discontinuous, parallel to undulating, medium amplitude, and low frequency reflections.

Figure 4. Lithostratigraphy and seismostratigraphy of the Chaleurs Bay Synclinorium and the Aroostook-Percé Anticlinorium. CB + MC: Corner of the Beach and Murphy Creek formations; NOM: Nadeau ophiolitic Mélange; MRM: Milieu River Mélange (modified from: Bourque et al., 2001; Jutras and Prichonet, 2002; Malo, 2004, De Souza et al., 2012; Marcil et al., 2005.)

3. Method

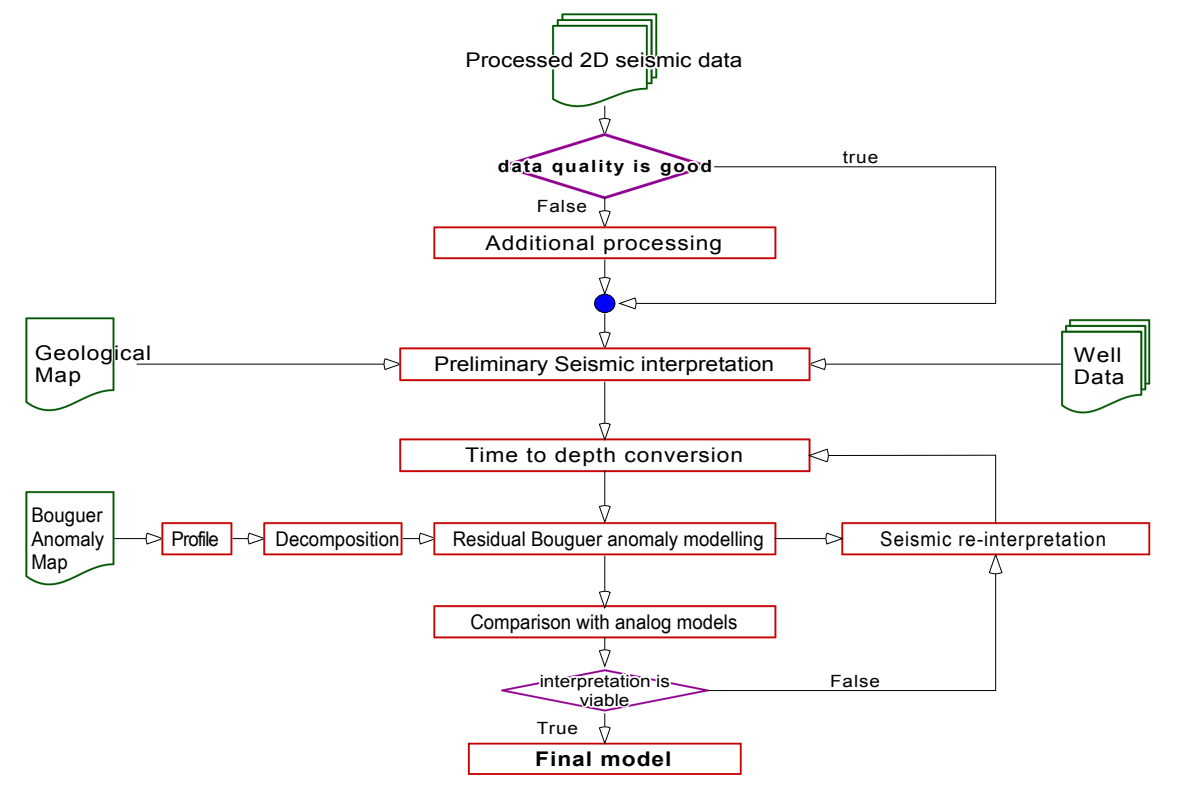


Figure 5. Working method used to produce the structural model of the study area. The seismic interpretation was constrained by the geological map and formation tops penetrated by well Paspébiac No. 1. The seismic interpretation was converted into depth by using interval velocities derived from velocity 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 and was later decomposed into a regional and a residual component by the visual adjustment method. The gravity model was constrained by measured densities of the units. 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.

4. 2D Seismic

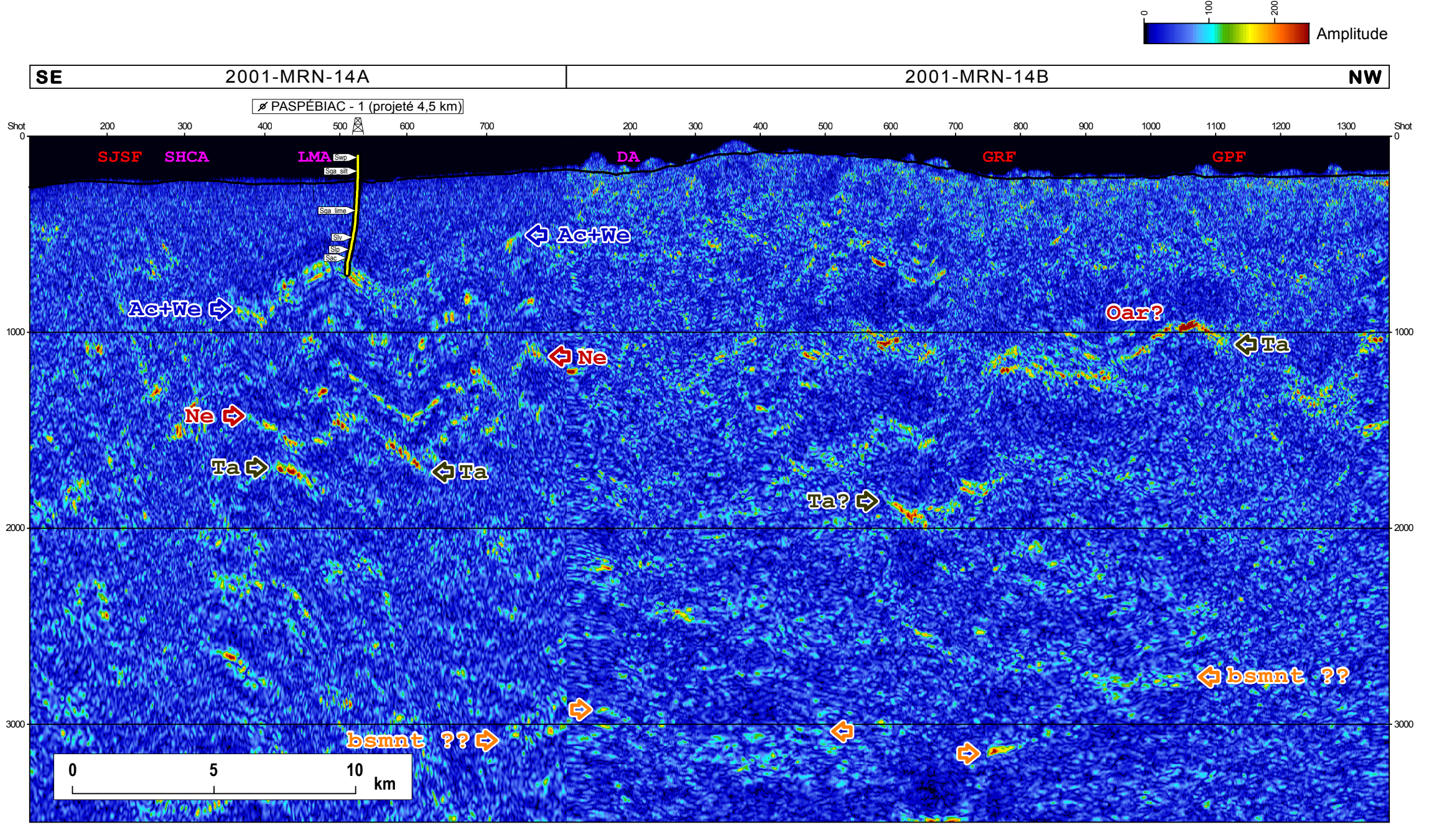


Figure 6. Envelope representation of pre-stack migrated 2001-MNR-14A and 2001-MNR-14B seismic lines. Ac-We: Anse-Cascon and Weir Fms; Ar: Arsenault Fm; Ne: Neckwick Fm. top; Ta: Taconic unconformity. For location, see figure 3.

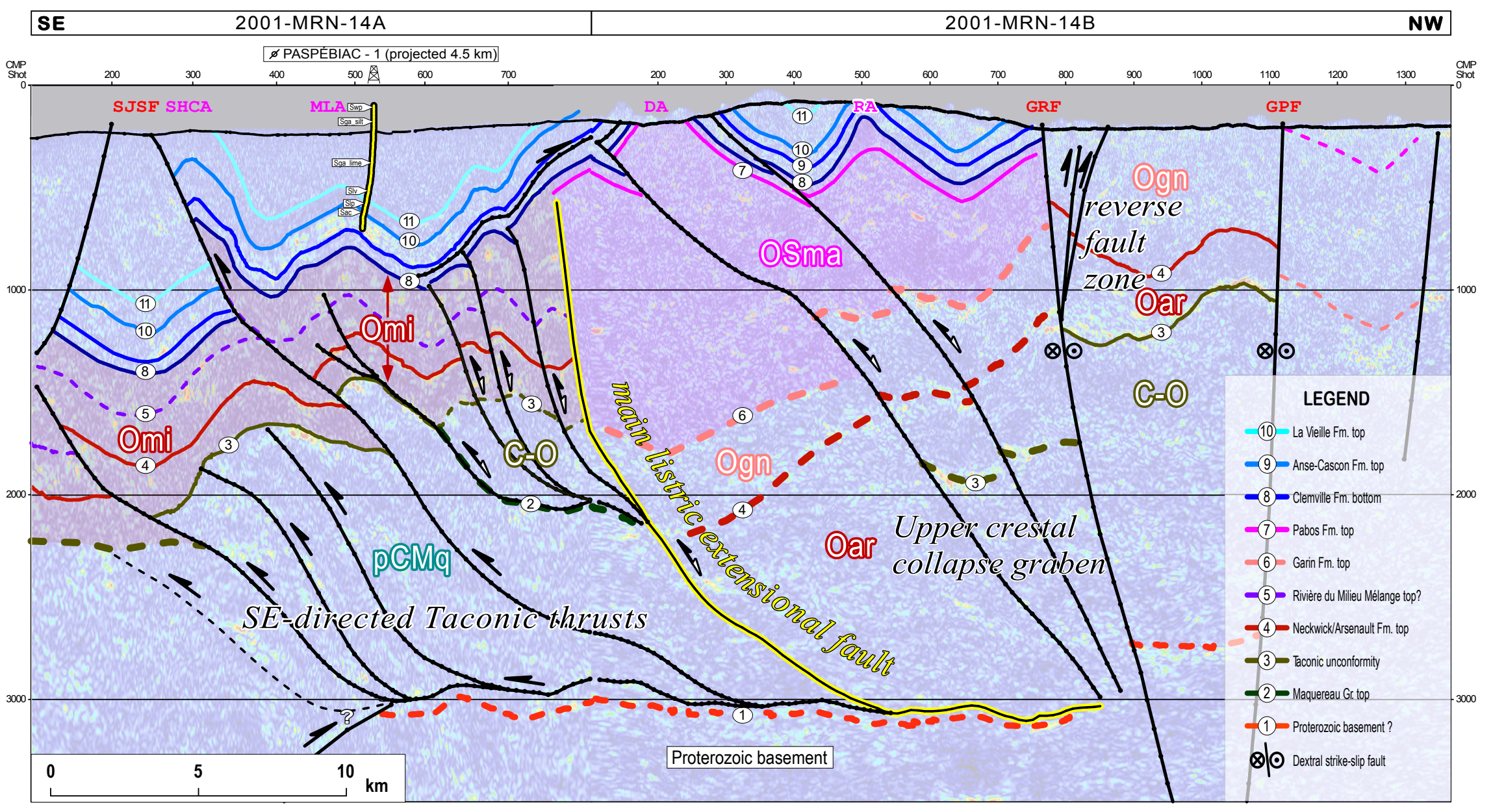


Figure 7. Structural interpretation of seismic lines 2001-MRN-14A and 2001-MNR-14B. DA: Duval Anticline; LMA: Lake Ménard Anticline; RA: Robidoux Anticline; SHCA: St-Hélène-de-la-Croix Anticline; SJSF: St-Jogues South Fault; GPF: Grand Pabos Fault; RGF: Garin River Fault; Oar: Arsenault Formation; Ogn: Garin Formation; Omi: Mictaw Group; OSma Matapedia Group. pCMq: Maquereau Group. For location, see figure 3.

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 on the Taconic unconformity 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).

5. Gravity Data Modeling

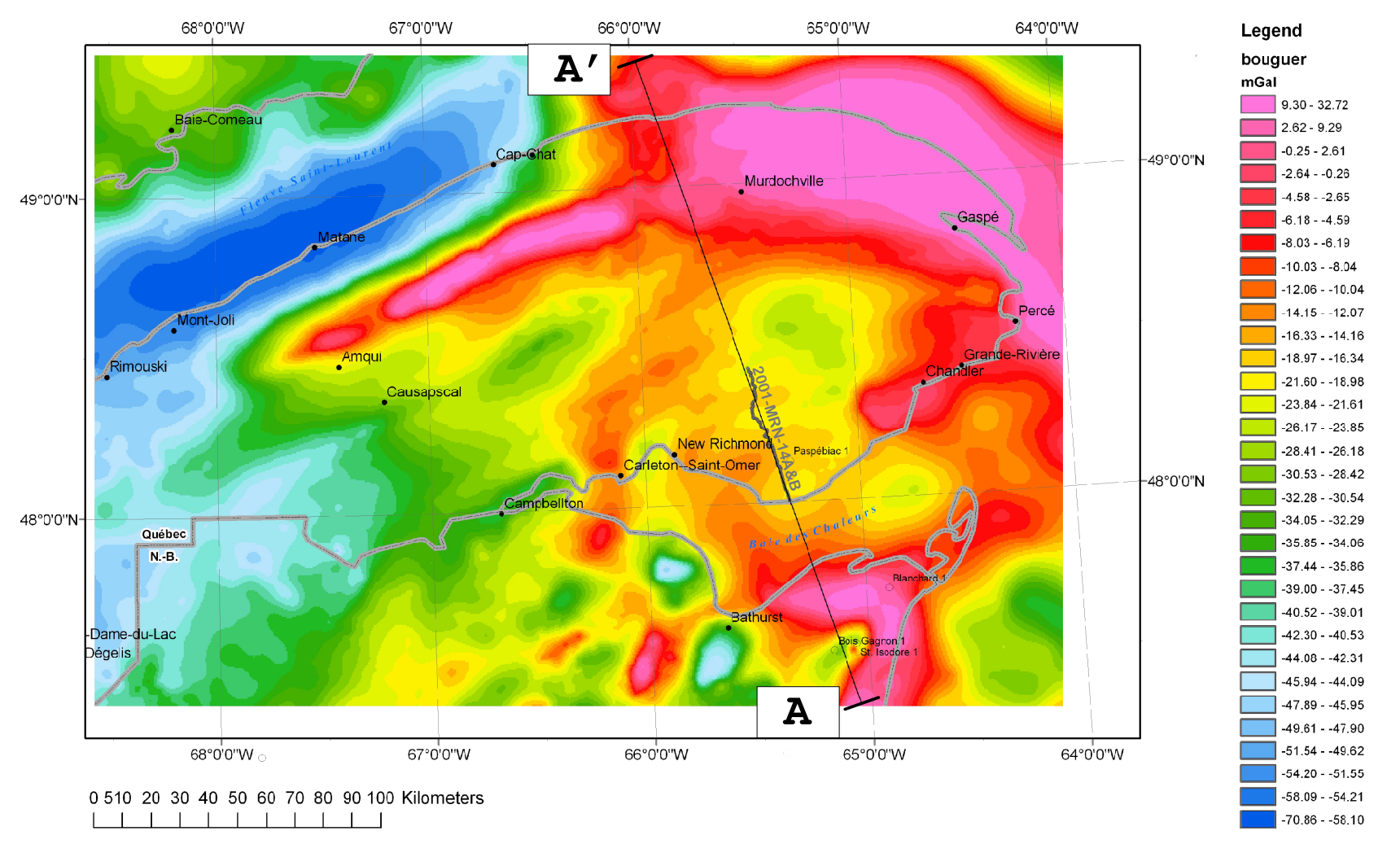


Figure 8. Location of the gravity profile and the seismic lines 2001-MNR-14A and 2001-MRN-14B in the Bouguer anomaly map of the Gaspé Peninsula (modified from: Pinet *et al.*, 2005).

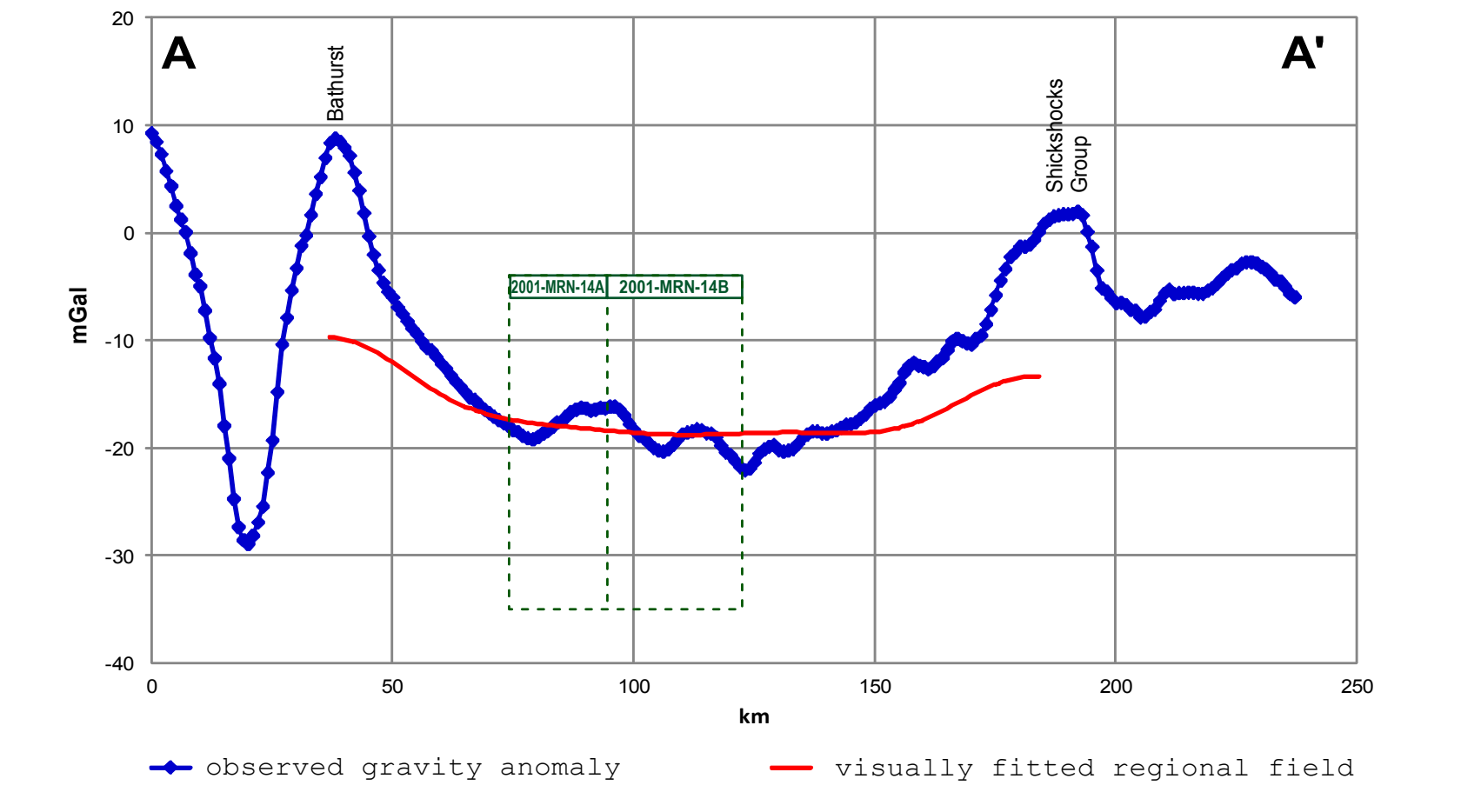


Figure 9. Observed gravity profile (total anomaly) extracted from the Bouguer anomaly map and visual estimation of the regional field.

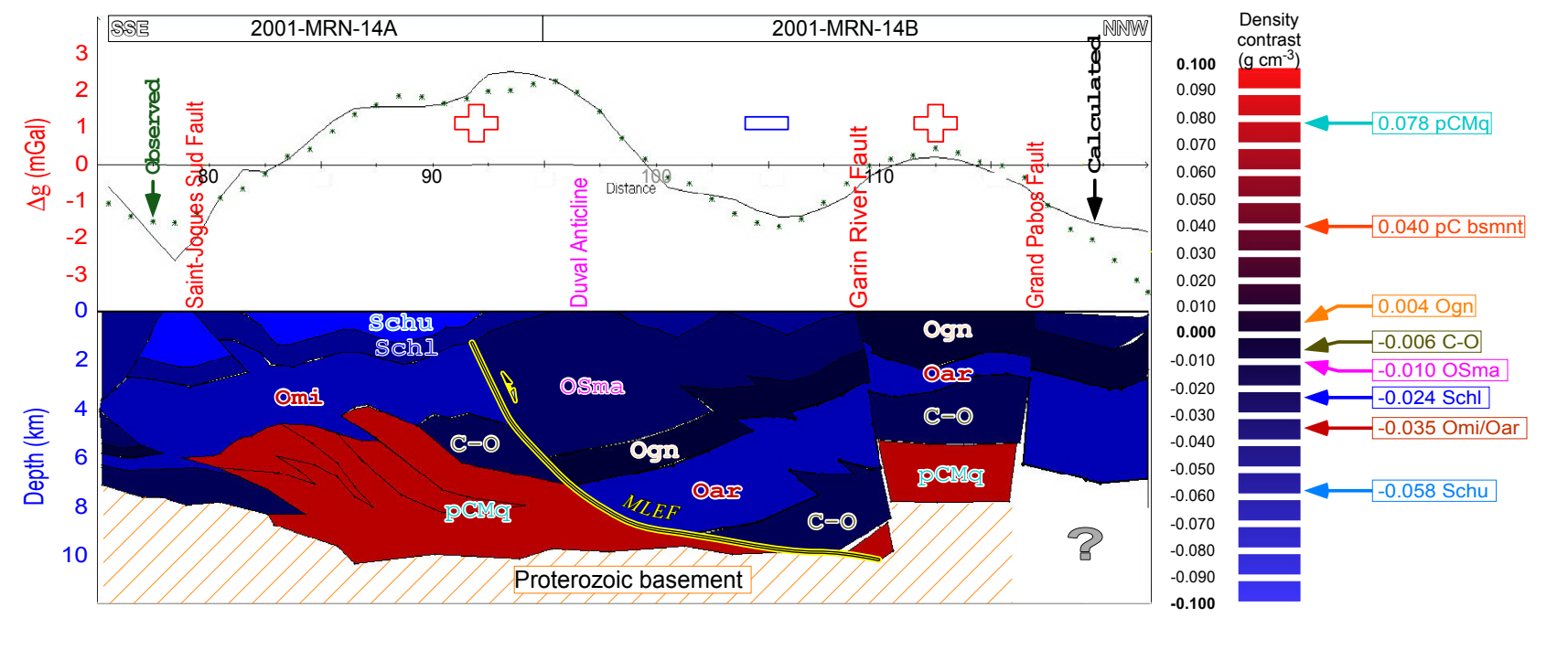


Figure 10. Gravity data modeling. C-O: non-metamorphosed Ordovician. MLEF: Main Listric Extensional Fault. pCMq: Maquereau Group. Oar: Arsenault Formation. Ogn: Garin Formation. Omi: Mictaw Group. OSma: Matapedia Group. Schi: Lower Chaleurs Group. Schu: Upper Chaleurs Group.

In the model, the positive (southern) anomaly is reproduced mainly through tectonic stacking 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, already 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.

6. Analog Model

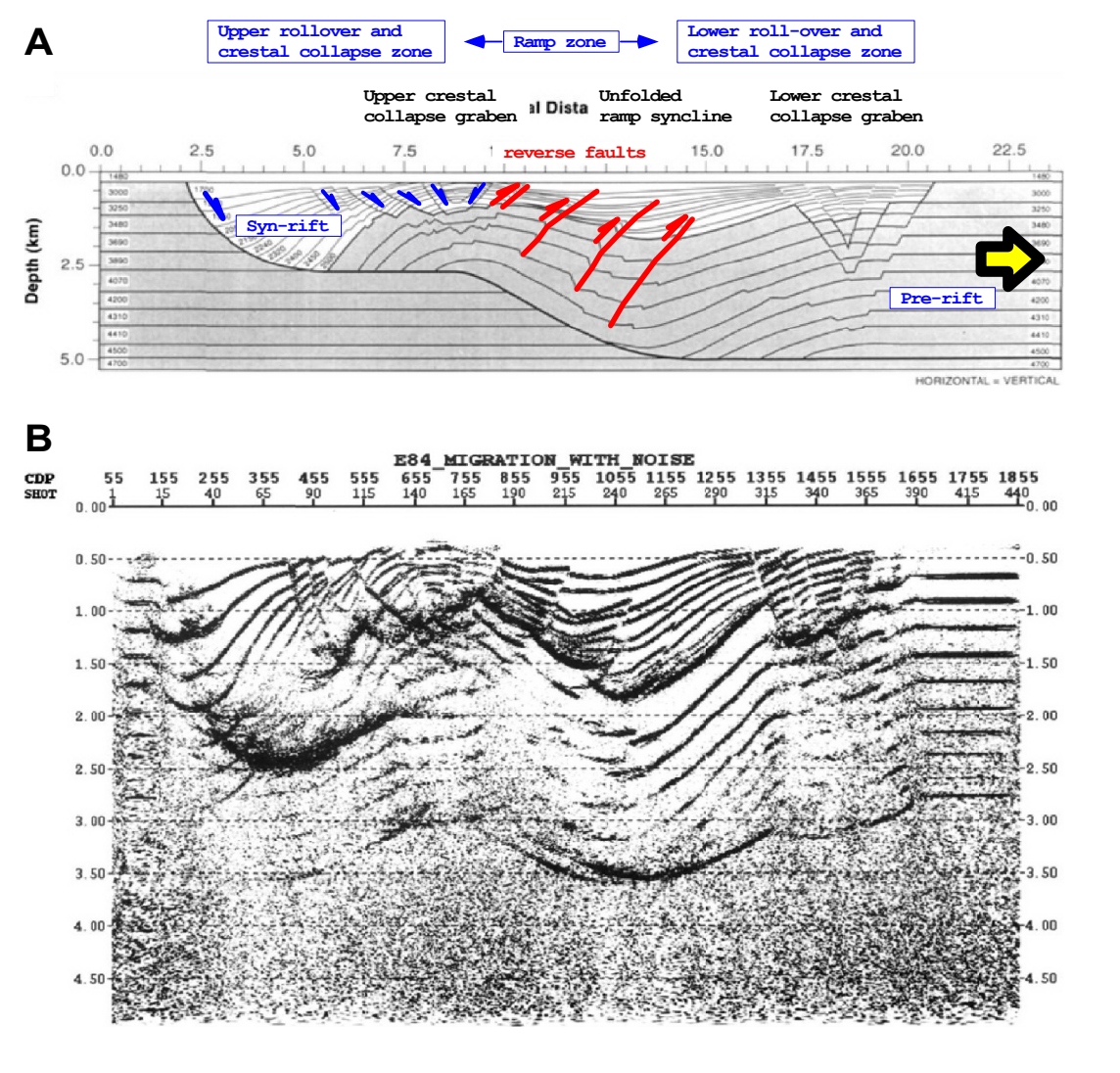


Figure 11. (a) Geometry and seismic velocity model of a ramp-flat listric extensional fault system. Pre-extension strata are shaded grey and syn-extension strata are unshaded. **(b)** Migrated synthetic seismic section (with noise) produced by the Stable Beam Method (modified from McClay, 1995).

7. Correlations with existing thermal maturity data

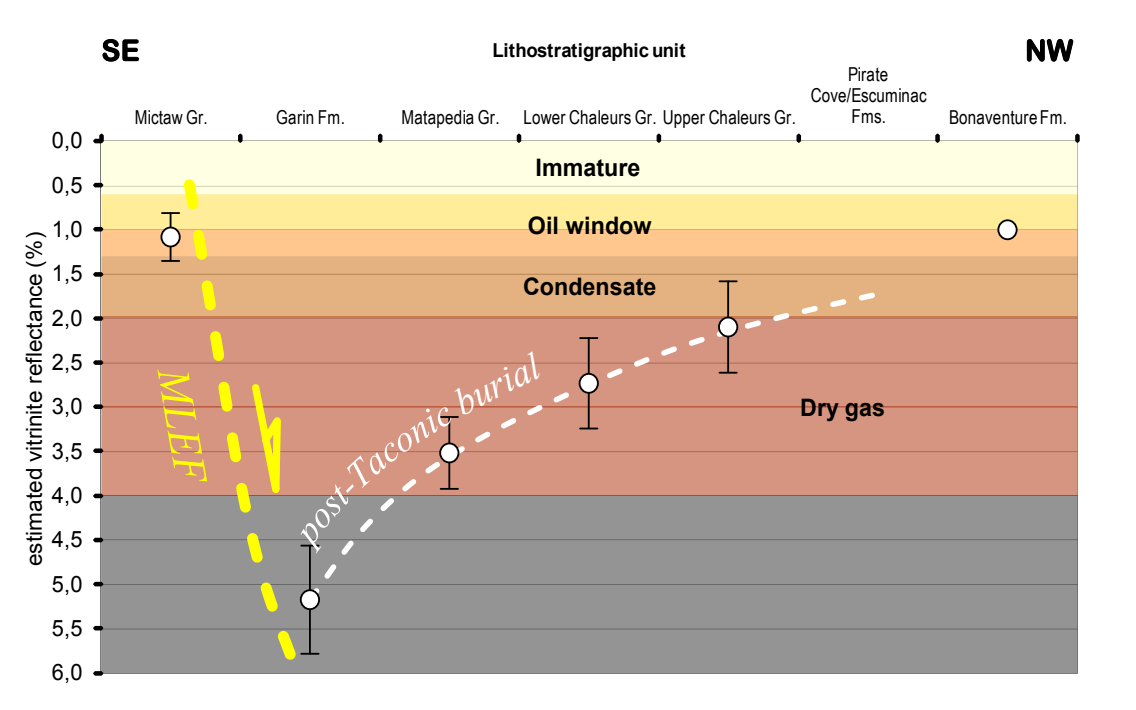


Figure 12. Variations in the average estimated vitrinite equivalent-reflectance values in different lithostratigraphic units of the Chaleurs Bay Synclinorium (Eastern area) and the Aroostook-Percé Anticlinorium (modified from Roy, 2008).

In the Chaleurs Bay Synclinorium, most of outcropping rock units are in the condensate to dry gas windows and exhibits 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 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 fault, were preserved from significant post-Taconic burial, while syn-extension strata were deposited during the post-Taconic extension phase, in the hanging wall (northwest) of this fault. For the CBS, the Ordovician Mictaw Group (Dubuc Formation) is a potential source rock of hydrocarbons, reaching TOC values higher than 3.0% with organic matter type II (Malo *et al.*, 2008; Roy, 2008).

8. Kinematics and Timing of Deformation

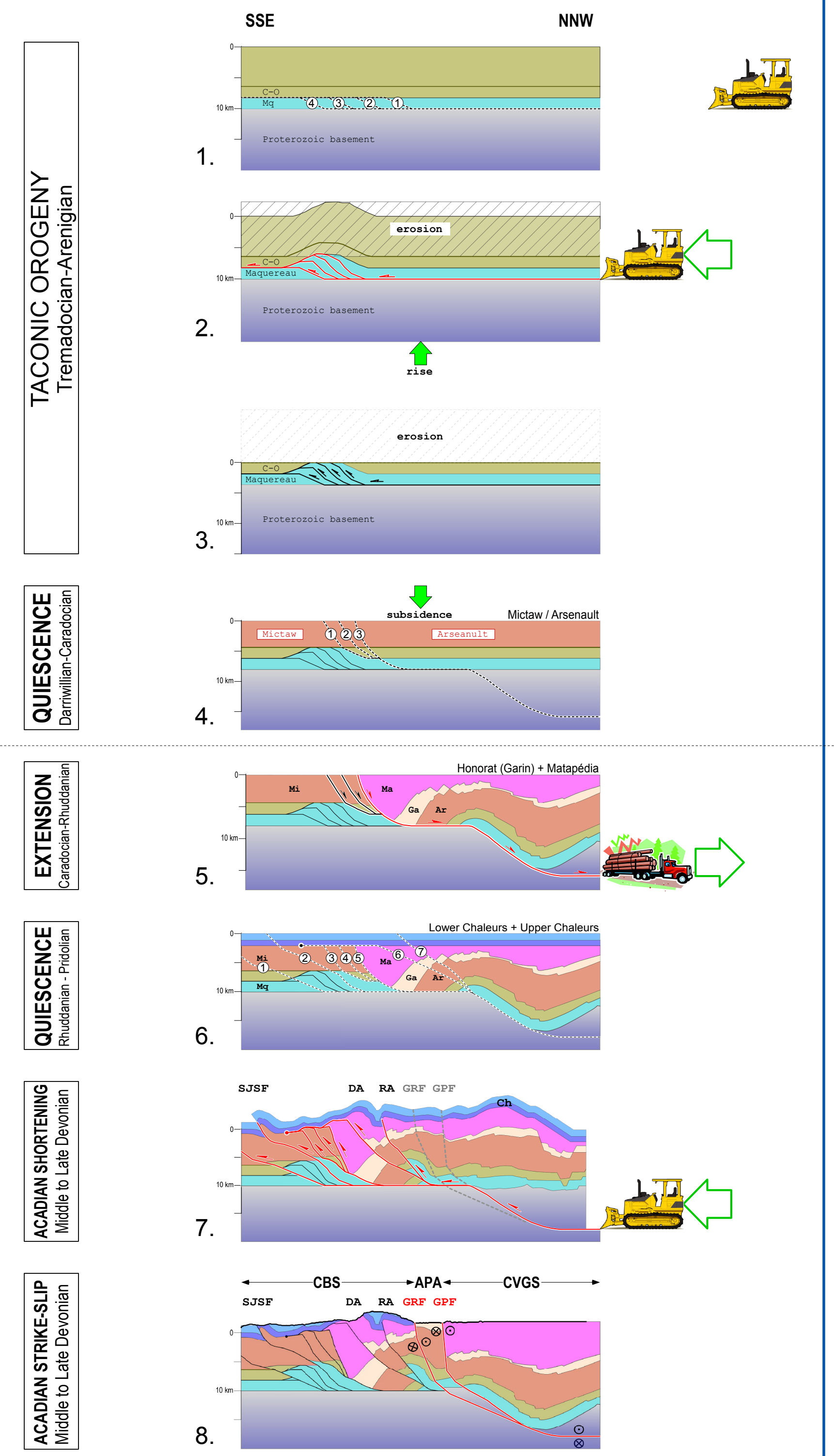


Figure 13. Structural evolution of the Chaleurs Bay Synclinorium and the Aroostook-Percé Anticlinorium. APA: Aroostook-Percé Anticlinorium; Ar: Arsenault Formation; CBS: Chaleurs Bay Synclinorium; Ch: Chaleurs Group; C-O: non-metamorphosed Cambro-Ordovician; CVGS: Connecticut Valley-Gaspe Synclinorium. 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.

The **Taconic orogeny** (Tremadocian-Arenigian, **figs 13.1 - 13.3**) is characterized by the emplacement of a SE-directed **hinterland dipping duplex** involving the Maquereau Group.

Time correlative Arsenault Formation and Mictaw Group are deposited during a relatively **quiescent interval** (Darriwillian-Caradocian, **fig 13.4**).

The **post-Taconic extension** (Caradocian-Rhuddanian, **fig 13.5**) 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.

The occurrence of a relatively **quiescent period** (Rhuddanian - Pridolian, **fig 13.6**) is supported by the relatively constant thickness and the absence of documented synsedimentary faults in the Chaleurs Group.

The **Acadian Orogeny** (Middle to Late Devonian) can be divided into two distinct phases: an early phase of shortening **(fig 13.7)**, followed by a late phase of dextral strike-slip faulting **(fig 13.8)**. 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.

9. 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 distinct 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; (4) the high organic content shales of the Mictaw Group, located in the footwall of the post-Taconian normal fault, experienced less burial than correlative rocks found in the hanging wall and preserved a significant hydrocarbon potential.

Acknowledgements

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