Structural Analysis and Kinematic Restoration along the Nova Scotia Passive Margin, Atlantic Canada

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Summary

The Atlantic-type continental margin offshore Nova Scotia passive margin represents the northern part of the 2000-km-long North American-African rifted system that formed during opening of the Central Atlantic Ocean initiated at the end of the Triassic period. The margin is characterized by longitudinal variation in crustal structure and amount of extension from the volcanic U.S. Atlantic Margin in the southwest to a non-volcanic Newfoundland Margin in the northeast. Tectonic and eustatic effects, type of salt deformation and magmatic underplating are recognized as principal components contributing to the variation of crustal structural styles of the offshore Nova Scotia (Watts and Steckler, 1979; Dehler & Keen, 1993). Therefore, this research carries out 2D structural interpretations of seismic data and 2D kinematic restoration reconstructions to quantify the variations in the amount of tectonic extension, subsidence, and isostatic response across and along the margin.

Data and Method

The seventy-seven wells with formation tops, well reports, well trajectories, log suites (GR, DT, RHOB, Resistivity, and Caliper), and checkshot surveys from CNSOPB (Canada-Nova Scotia Offshore Petroleum Board) were made available for this project. In addition, 10 000 km of six 2D seismic surveys, four of which are in the time domain, two others are both time and the depth domain, and a 3D seismic cube in time domain were also provided for this project (Figure 1).

For the purpose of structural analysis and kinematic restoration along the passive margin, we first interpreted faults and horizons along 2D regional seismic lines by integrating them with published topographic, gravity and aeromagnetic surveys in the Petrel software. Afterwards, we carried out the 2D sequential restoration of deformation of Mesozoic-Cenozoic sedimentary succession of the Scotia Basin along four NW-SE-striking seismic profiles (1100, 1400A, 1600, and 2000 NovaSPAN lines) in the Move suite of Petroleum Experts. The restoration for each time step involves restoring fault offset, unfolding, thermal subsidence, isostasy, and decompaction. The effects of salt movement on the overlying unit is restored. An estimation of the amount of tectonic extension and quantifying the variations in the amount of thermal subsidence and isostatic response across the Nova Scotia passive margin is performed for each time step along four NW-SE cross-sections.

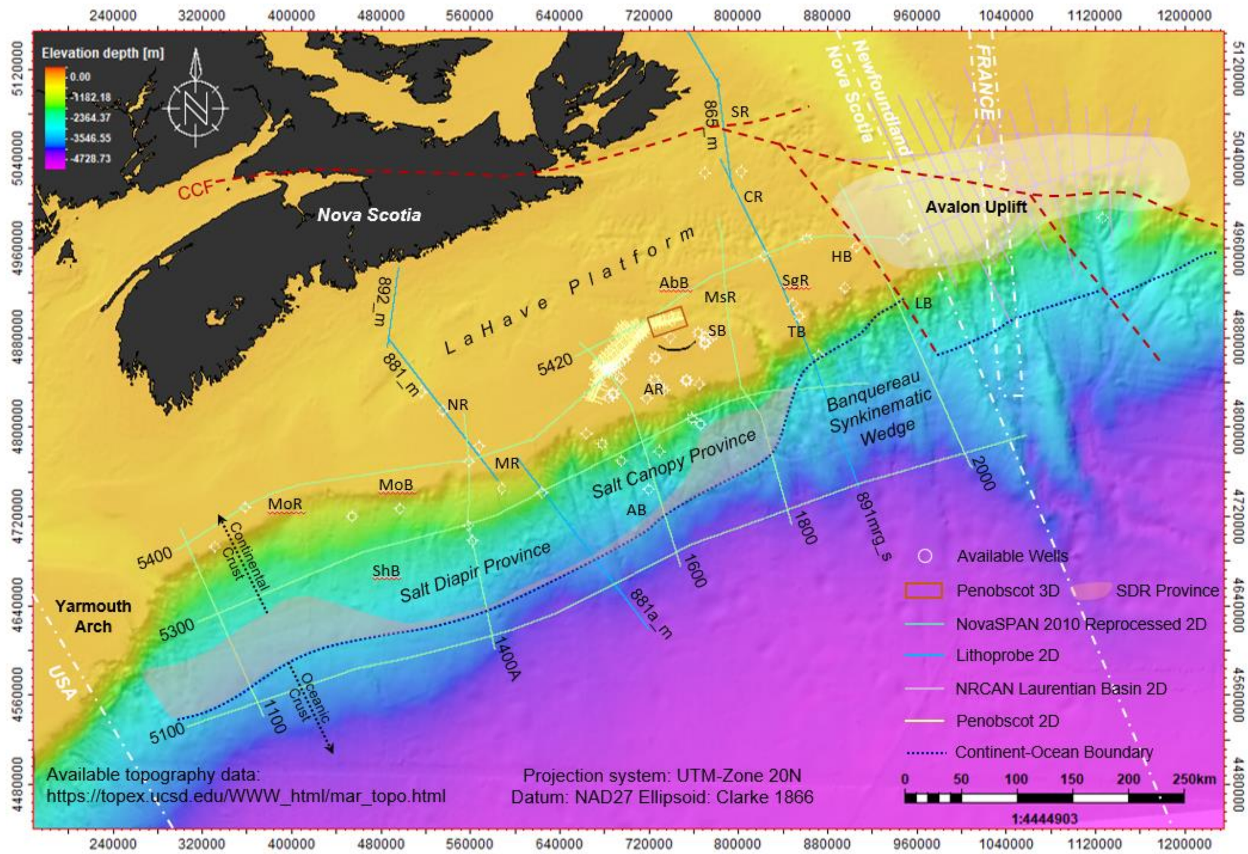

Figure 1: The shaded relief bathymetry of the study area, depicting structural provinces, subbasins and ridges, available seismic surveys and well data. AbB: Abenaki Subbasin, AB: Annapolis Subbasin, AR: Alma Ridge, CR: Canso Ridge, HB: Huron Subbasin, LB: Laurentian Subbasin, MoB: Mohican Subbasin, MoR: Mohawk Ridge, MR: Moheida Ridge, MsR: Missisauga Ridge, NR: Naskapi Ridge, SB: Sable Subbasin, SgR: South Griffin Ridge, ShB: Shelburne Subbasin, SR: Scaterie Ridge, TB: Tantallon Subbasin, CCF: Cobequid-Chedabucto Fault.

Results

In this study, five different sets of normal faults interpreted on seismic profiles are identified in the Nova Scotia margin (Figure 2). (1) NE-SW-striking syn-rift normal faults in the acoustic basement veneered by a thin autochthonous salt correspond to the onset of continental breakup during the Triassic and Early Jurassic. The geometry of the syn-rift faults remarkably varies across the Nova Scotia passive margin. The faults are planar in the upper crust below the continental shelf and slope dipping both to the NW and SE. The SE-dipping normal faults in the basement are listric and merge into a flat detachment at ~12 km of depth in deep-water settings. Some of the listric faults in the eastern segment of line 2000 are reactivated resulting in small-scale displacement of Jurassic and Cretaceous units. (2) SE-dipping listric faults and rollover anticlines developed in the Upper Jurassic strata in a distal part of the basin, merging into a detachment along thin allochthonous salt canopy propagated to the southeast. (3) SE-dipping normal faults in Cretaceous units are associated with salt remobilisation and gravitational sediment loading in slope setting (Figure 2b). The salt bodies were remobilized during the Cretaceous-Tertiary, and widespread turtle-structures and minibasins were transported basinward above the canopy across the province (Figure 2A). (4) The youngest faults are a set of small-scale conjugated normal faults associated with crestal deformation in Tertiary deposits above salt diapirs (Figure 2A). According to the structural interpretation results, the mobilization of salt triggered by several periods of sediment loading and gravity gliding shapes the structural morphology of the Nova Scotia margin.

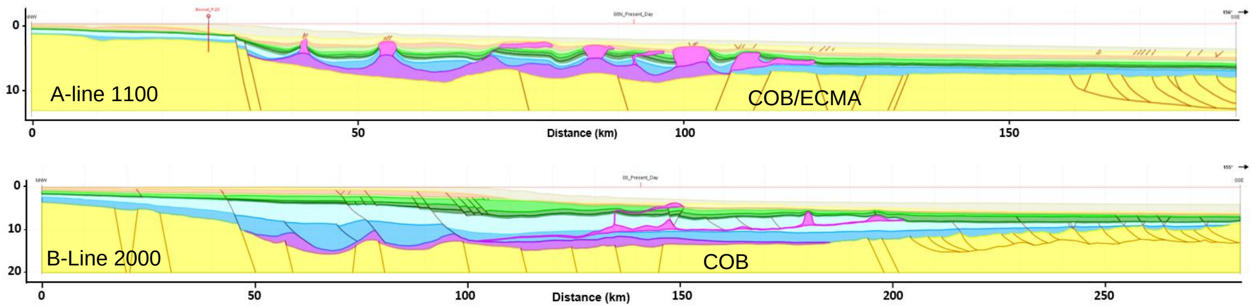

Figure 2: Structural interpretation in depth domain (Z scale is in km) along the NW-SE striking Line 1100 (A) and Line 2000 (B) located in the SW and NE segments of the Nova Scotia Basin, respectively (Fig. 1). Different sets of faults are recognized across the margin in continental shelf, slope and in deep basin of the oceanic domain. COB: Continent-ocean boundary, ECMA: East Coast Magmatic Anomaly.

The extension amount of 1.55% along the cross-section in the SW segment of the margin is predominantly accommodated by syn-rift-related listric faults. In contrast, both syn-rift faults and Cretaceous faults contribute to the extension in the NE segment of the margin, where the extension amount achieves 3.75%. Besides, the effect of Tertiary faults representing the deformation in the Cenozoic on the extension amount is only 0.1% at most.

The thermal subsidence of each seismic marker is not constant along the profiles, and it increases seaward. Initial rapid thermal subsidence by the end of the rifting stage has been followed by slow post-rift thermal subsidence for each seismic marker along all four cross-sections. In the northeastern segment of the margin, the maximum thermal subsidence of 1000 m is reconstructed in the deep-water setting and of ~100-200 m in the shelf area by the end of rifting (J200). The thermal subsidence for the post-rift units is ~30 m in the shelf and increases ~300 m in the deep basin. In the southwest of the margin, the thermal subsidence of ~150 m at the shelf and of ~750 m at the oceanic domain are reconstructed for the rifting stage (J200). Similarly, post-rift subsidence varies from ~50 m at the shelf to ~250 m at the deep-water setting.

The estimated decompaction and isostatic rebound are more significant in the depocenters with higher subsidence rates. The isostatic rebound is reconstructed up to 2500 m below the present-day shelf for the Jurassic strata in the NE segment of the margin. During that time, salt mobilization results in S- and SE-dipping faulting and more accommodation in main depocenters (Figure 3, J163). On the other hand, during Cretaceous and Tertiary time, the maximum isostatic rebound of ~500 m is reconstructed in the slope area, where S- and SE-dipping normal faults have been formed as a result of gravitational sediment loading in the slope setting (Figure3, T50 and K101). Toward the southwest of the margin, lesser amount of the isostatic rebound is reconstructed for each seismic markers. In contrast to the NE segment of the margin, the isostatic rebound of Jurassic units along Line 1100 is about 580 m and it is localized mostly in the area of the continent-oceanic transition (COB) and ECMA. The isostatic response of younger units along this line is ~300 m, whose sedimentation was governed by remobilisation of salt diapirs and emplacement of mini-depocenters between them.

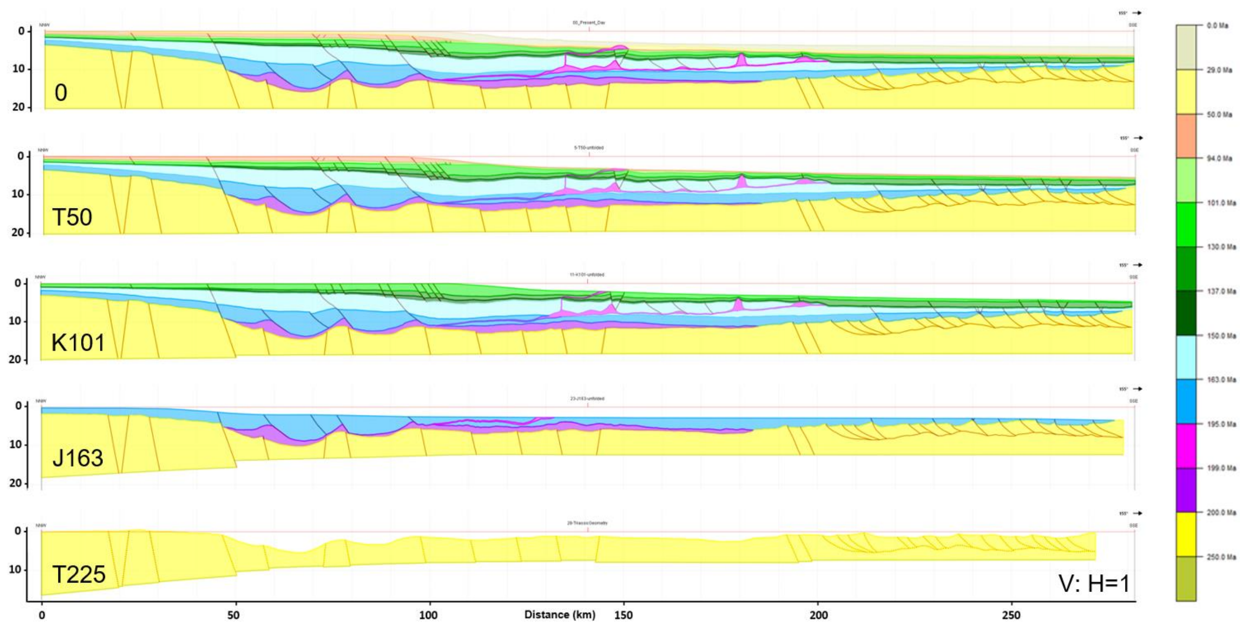

Figure 3: The 2D kinematic restoration of the Line 2000 in depth domain. Vertical scale is in km.

Conclusions

The Mesozoic and Cenozoic sedimentary succession in the southwestern volcanic segment of the Nova Scotia margin is less faulted than it is in the northeastern non-volcanic segment of the margin. Therefore, the estimated amount of extension varies across the margin, gradually increasing from 1.55% in the SW to 3.75% in the NE. Most of the extension is associated with the syn-rift normal faulting in the acoustic basement. Additionally, the SE-dipping Cretaceous growth faults also contribute to the extension in the northeastern segment. Along the NW-SE striking lines, the maximum amount of extension is reconstructed in the deep-water basin of the oceanic domain, while only small portion of extension is accommodated by the planar normal faults in the area if the continental shelf and slope.

The amount and distribution of thermal subsidence vary across the margin; it increases basinward for each seismic marker. The maximum thermal subsidence is reconstructed at the end of the rifting stage in four cross-sections. The subsidence of each seismic marker exhibits a gradual increase in the SW segment of the margin, and the maximum amount reaches ~750 m. In contrast, the subsidence is ~1000 m in the northern segment of the margin and it is characterized by strong gradient in the area of the continental slope for each seismic marker.

The salt mobilization, faulting, and sediment loading vary along the Nova Scotia passive margin. The total thickness of sedimentary succession increases from 5-8 km in the south to 14-18 km in the north, where increased sediment loads and salt kinematics mainly control the subsidence rate and associated isostatic rebound. In the northeastern part of the margin, normal faulting and a high degree of crustal extension and thinning accommodate main depocenters. The maximum isostatic rebound of Jurassic and younger units is reconstructed close to the shore, below the present-day shelf. Towards the southwest, no visible correlation is observed between high isostatic responses and sediment load in Jurassic units. Instead, the ECMA likely determines the localization of isostatic rebound in the Jurassic units. For the younger units, sediment load and localization of mini-basins accommodated by remobilization of salt diapirs are the driving mechanisms for higher isostatic responses similar to the northeastern part of the margin.

Acknowledgements

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