REGIONAL GEOLOGY OF THE SCOTIAN BASIN

David E. Brown, CNSOPB, 2008

INTRODUCTION

The Scotian Basin is a classic passive, mostly non-volcanic, conjugate margin. It represents over 250 million years of continuous sedimentation recording the region's dynamic geological history from the initial opening of the Atlantic Ocean to the recent post-glacial deposition. The basin is located on the northeastern flank of the Appalachian Orogen and covers an area of approximately 300,000 km^2 with an estimated maximum sediment thickness of about 24 kilometers. The continental-size drainage system of the paleo-St. Lawrence River provided a continuous supply of sediments that accumulated in a number of complex, interconnected subbasins. The basin's stratigraphic succession contains early synrift continental, postrift carbonate margin, fluvial-deltaic-lacustrine, shallow marine and deepwater depositional systems.

PRERIFT

The Scotian Basin is located offshore Nova Scotia where it extends for 1200 km from the Yarmouth Arch / United States border in the southwest to the Avalon Uplift on the Grand Banks of Newfoundland in the northeast (Figure 1). With an average breadth of 250 km, the total area of the basin is approximately 300,000 km^2. Half of the basin lies on the present-day continental shelf in water depths less than 200 m with the other half on the continental slope in water depths from 200 to >4000 m.

The Scotian Basin formed on a passive continental margin that developed after North America rifted and separated from the African continent during the breakup of Pangea (Figure 2). Its tectonic elements consist of a series of platforms and depocentres separated by basement ridges and/or major basement faults. From the southwest to the northeast, these elements are identified as the Shelburne Subbasin, LaHave Platform, Sable and Abenaki Subbasins, Banquereau Platform, Orpheus Graben and Laurentian Subbasin, and its easternmost extension on the Burin Platform of Newfoundland’s Western Grand Banks (Figure 1). The boundaries of these platforms and basins probably represent extensions / projections of regularly spaced oceanic fracture zones onto continental crust (Welsink et al., 1990). A northeast-trending basement hinge zone is also present along the margin, defining the landward limit of maximum tectonic extension and an abrupt seaward increase in basement depth due to thermal subsidence (Figure 3). Together, these basement elements asserted a strong control on sediment distribution in the region for more than 190 million years.

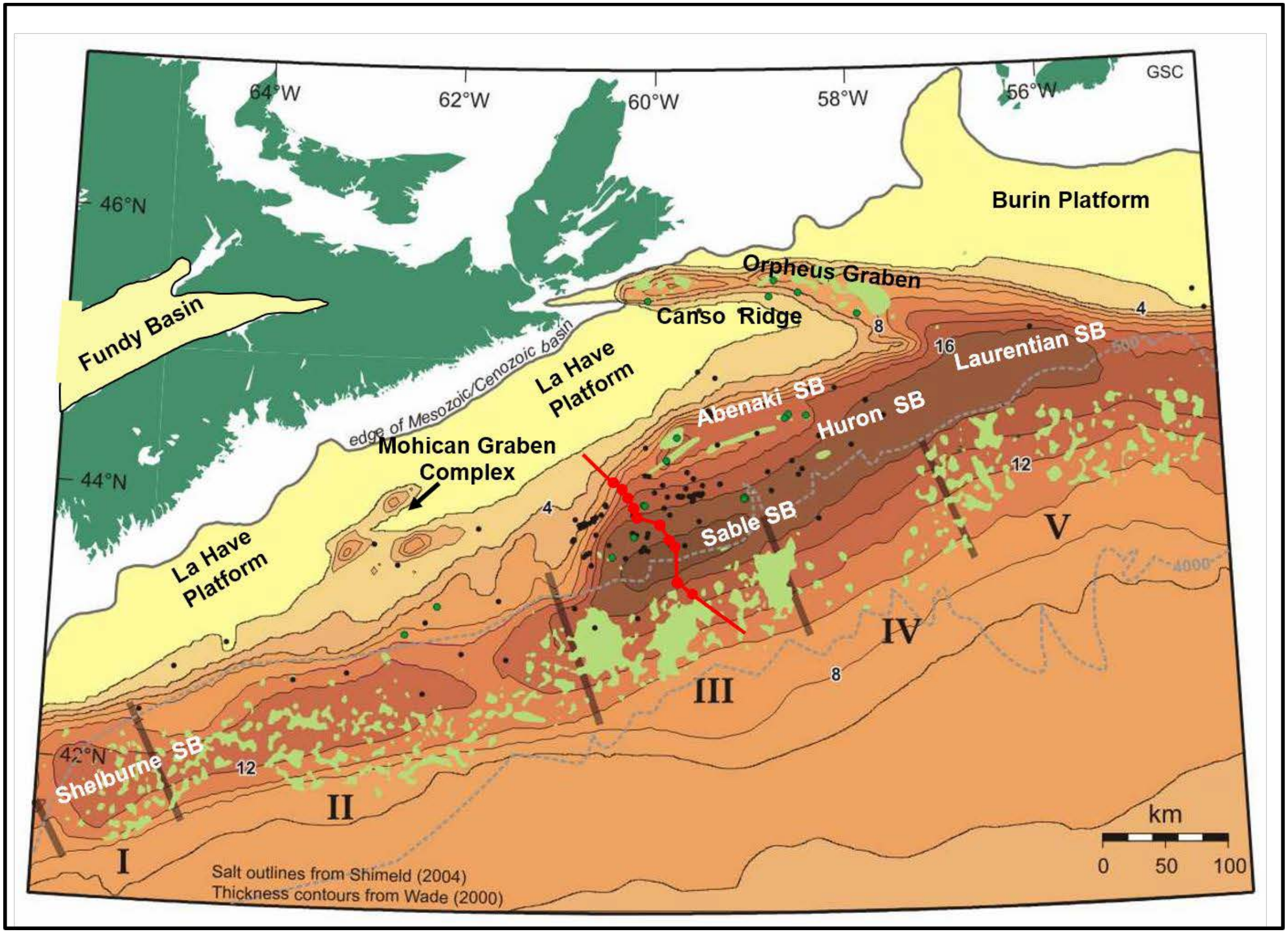


Figure 1. *Major tectonic elements of the Scotian Basin showing depth to basement in kilometers and bathymetric contours in grey. The black dots are industry wells, with the green dots those penetrating salt. The pale green areas represent earliest Jurassic (Hettangian) Argo Formation salt structures, with the Roman numerals indicating the salt / basement regions as defined by Kidston et al. (2002) and Shimeld (2005). The red line identifies the trace of the regional composite seismic profile in Figure 3 and red dots the intersected wells. Copyright © Geological Survey of Canada Atlantic - used with permission.*

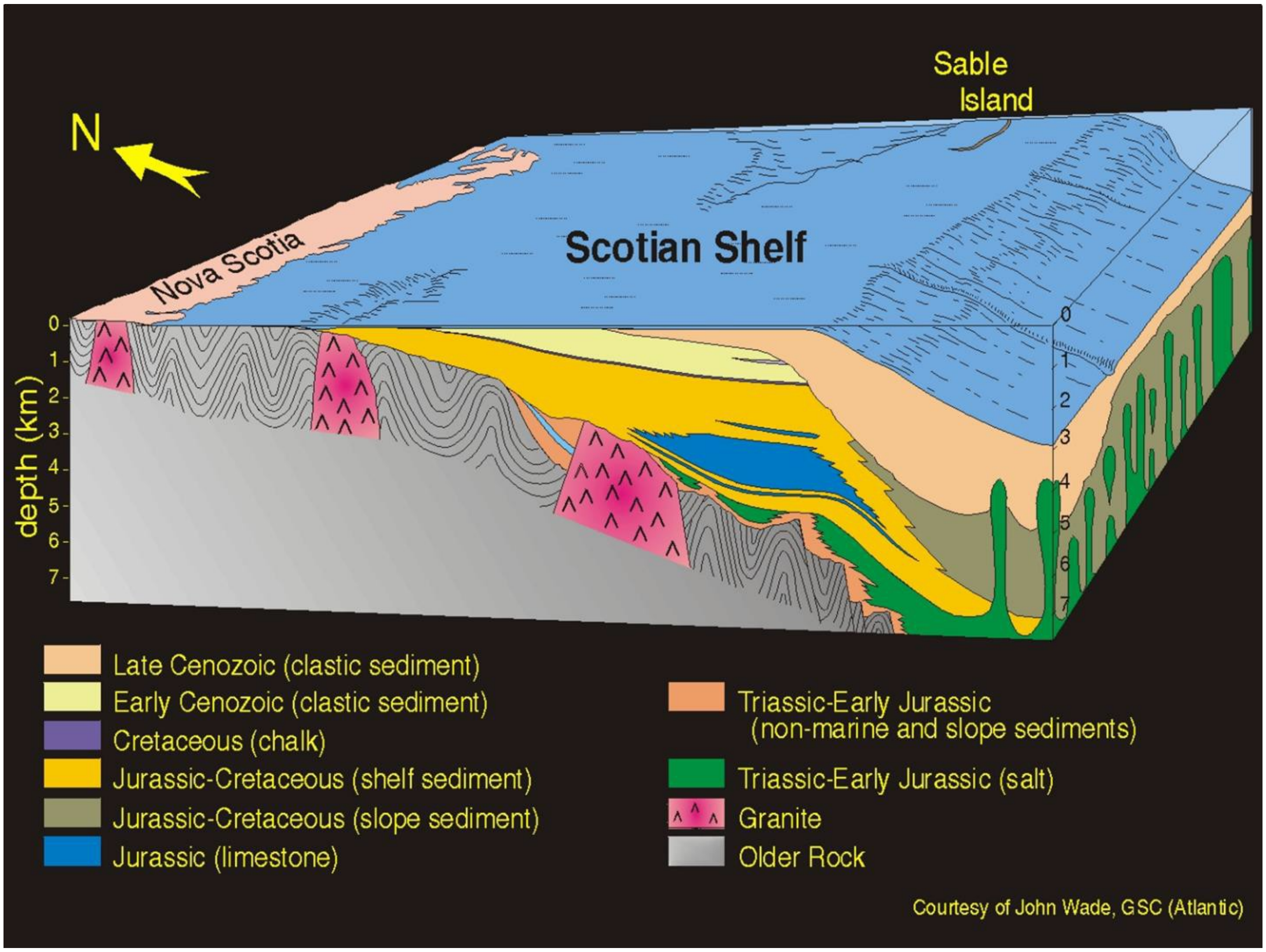
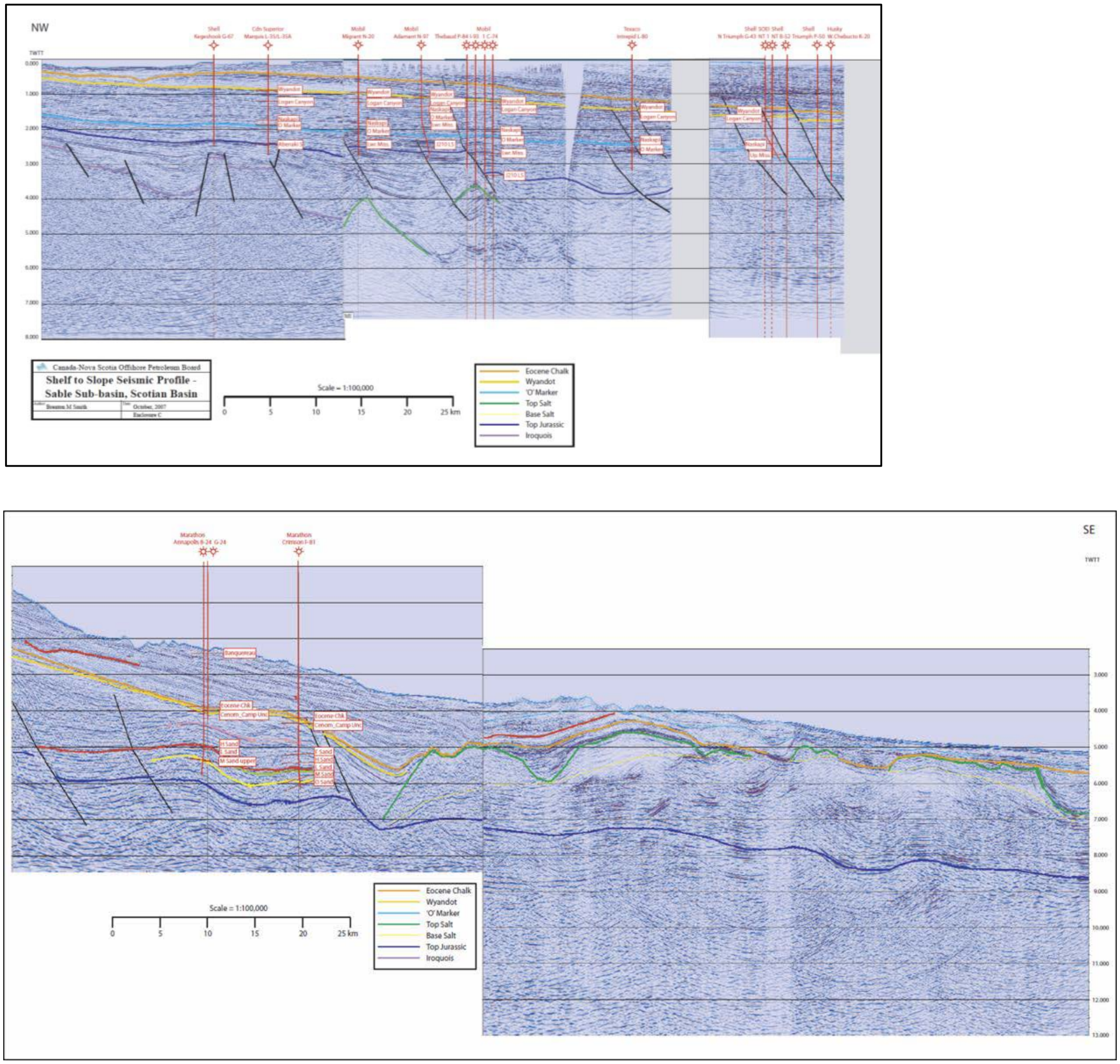


Figure 2. *Isometric view of the western portion of the Scotian Basin, offshore Nova Scotia. The representation of the Late Triassic-Early Jurassic Argo salt's distribution and thickness are exaggerated in this view. Copyright © Atlantic Geoscience Society - used with permission.*

SYNRIFT

Redbeds and evaporates were the dominant deposits during the late prerift phase, whereas typical clastic progradational sequences with periods of carbonate deposition dominated the drift phase (Figure 4). Rifting began in the Middle Triassic Period, about 225 million years ago (Ma). At that time, the Nova Scotia region occupied a near equatorial position, situated adjacent to its Morocco conjugate, with most of its older Paleozoic rocks having direct Moroccan / NW African affinities (Schenk, 1997). A series of narrow, interconnected rift basins were created by crustal attenuation during the initial rift phase, filled with fluvial and lacustrine red bed sediments, and capped by extrusive volcanic rocks (Fundy-type sequences). By the latest Triassic-earliest Jurassic, tectonic motion had moved the North American and African plates slowly northward, with the Nova Scotia-Moroccan region in an arid sub-equatorial climate zone (ca. 10°-20°N paleo-latitude). Renewed stretching and rifting of continental crust further to the north and east in the Grand Banks / Iberia region breached topographic barriers and permitted the first incursions of marine waters from the eastern Tethys paleo-ocean to flood into these interconnected synrift basins (Figure 5). Restricted, shallow marine conditions were established with mixed terrestrial and shoreline clastic and minor evaporite and carbonate sedimentation (Eurydice Formation). Due to the hot and dry climate, the shallow seas were repeatedly evaporated, resulting in the precipitation of extensive salt and minor anhydrite deposits that were as much as two kilometers thick in the central parts of the rift system (Argo Formation).



[Figure 3. (Click to download larger version of Figure)](#) *Composite seismic section across the Sable Subbasin, with the track shown in Figure 1. This 200 km composite profile starts landward of the Jurassic carbonate bank, runs across the Sable Subbasin through several gas fields, over the modern shelf break (top image), then down the slope across the Annapolis and Crimson deepwater wells, and out into the salt canopy complex (bottom image). The profile is composed of the following data sets and used with the kind permission of the respective organizations (from west to east): Canadian Superior Marquis 2D (Geophysical Service Incorporated), ExxonMobil Mega-Merge 3D (ExxonMobil), ExxonMobil North Triumph 3D (ExxonMobil), Marathon 3D (CGG Veritas) and the TGS Regional 2D (TGS-NOPEC). This line is described in detail by Kidston et al. (2007). A larger version provided as a separate attachment to this document.*

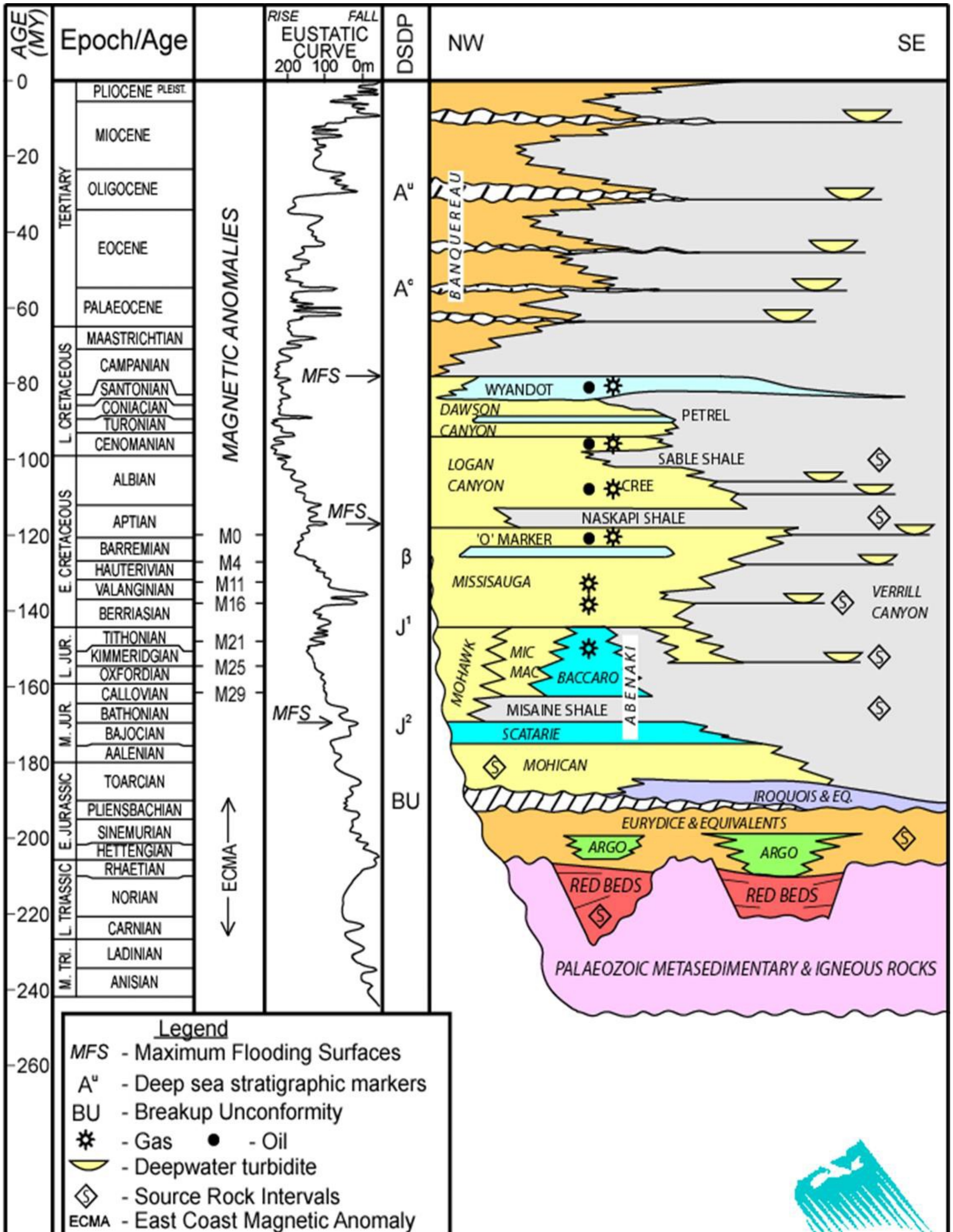


Figure 4. *Generalized stratigraphic column for the Scotian Basin, offshore Nova Scotia (CNSOPB). Detailed stratigraphic columns for the three Nova Scotia and Western Grand Banks of Newfoundland regions of the basin are published in Wade & MacLean, (1990). Sea level curve from Haq et al. (1987).*

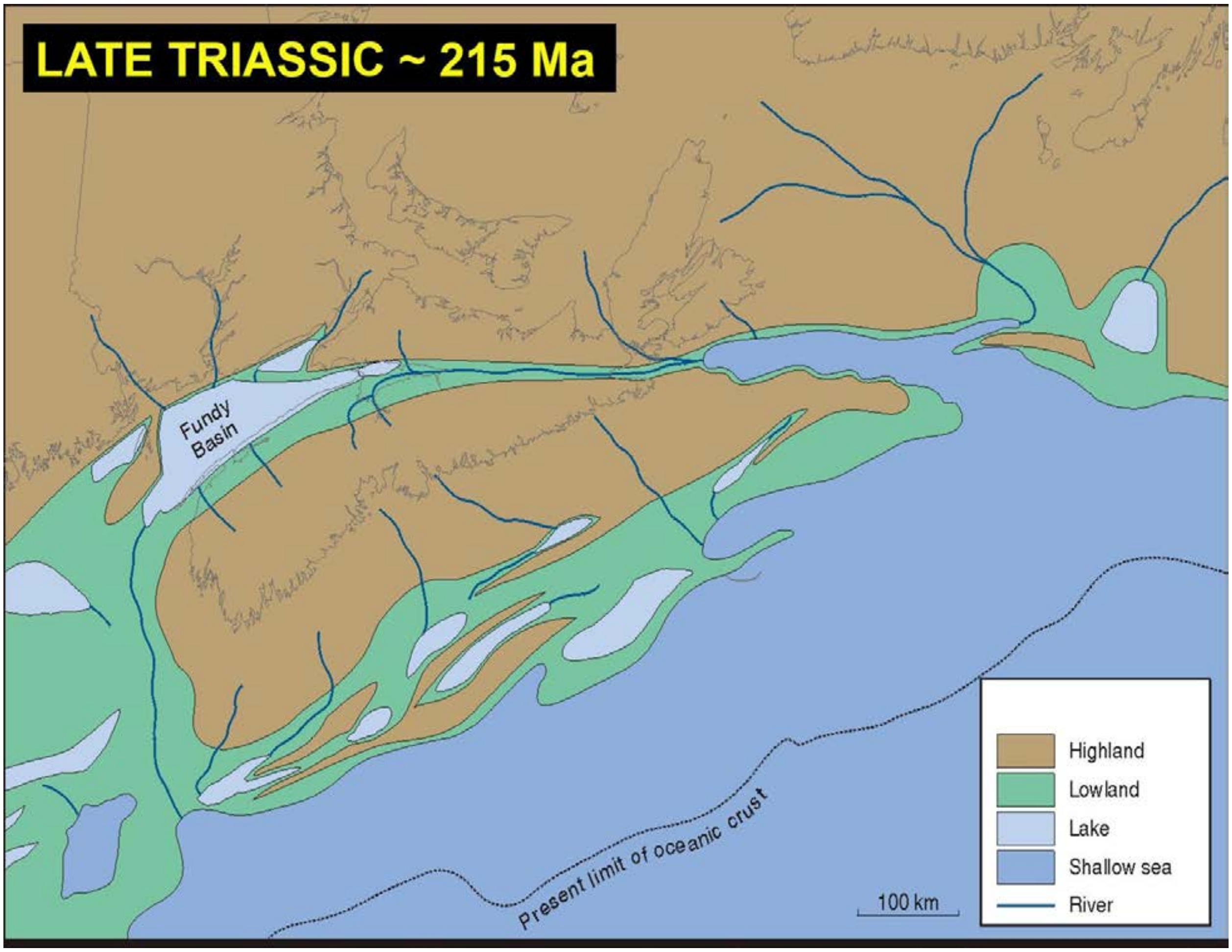


Figure 5. *Simplified paleogeographic reconstruction of the Scotian Basin during the Late Triassic (Norian) ca. 215 Ma. Salt deposition probably initiated during this period although on a much smaller scale than illustrated here. Argo Formation evaporites of this age are unconfirmed in the Nova Scotia part of the basin but present on the southeast Grand Banks and known as the Osprey Formation. Copyright © Atlantic Geoscience Society - used with permission.*

Earliest Jurassic siliciclastic deposition is observed in the west-central part of the Scotian Basin that may exist elsewhere along the margin and Moroccan conjugate. This eastward-directed pulse of redbed sediments (Heracles Unit; Brown, 2007) conformably overlies and deforms through loading Argo Formation evaporites in the Mohican Graben. The west-dipping listric faults inboard of the margin hingeline on the Mohican and Naskapi grabens reflect the antithetic response to extension in the large Fundy Basin far to the northwest during the Late Triassic (Wade et al., 1996). These grabens acted as loci for clastic deposition of newly established fluvial drainage systems, with the sediment source from the current mainland region of Nova Scotia. While not yet encountered in wells or observed elsewhere along the margin, the age of this succession can be reasonably inferred as early Hettangian to perhaps mid- to late Sinemurian since it conformably overlies the Argo Formation and is later truncated by the subsequent Breakup Unconformity described below.

Renewed tectonism in the central rift during the Early Jurassic (mid-Sinemurian) is recorded by complex faulting and erosion of Late Triassic and Early Jurassic sediments, and older Paleozoic basement rocks.

This phase of the rifting process is expressed as a diachronous Breakup Unconformity (BU). This coincided with the final separation of the North America and Africa continents, the creation of true oceanic crust through volcanism, and opening of the proto-Atlantic Ocean. Following this, the heavily faulted, complex terrane of fault-bounded grabens and basement highs along the Scotian margin underwent a significant degree on peneplanation and infilling.

EARLY POSTRIFT

Marine transgression above the BU eventually covered the basin with a narrow, shallow and restricted sea within which thin sequences of carbonates, siliciclastics, and minor evaporites accumulated. Deposition of transgressive shallow water to tidally influenced dolomites and siliciclastics occurred in localized areas on the seaward portion of the margin under variably restricted marine conditions (Iroquois Formation). Concurrently, a thick succession of coarser grained clastic sediments and shales from fluvial sources (Mohican Formation) was deposited on the basin margins sourced from adjacent high relief terranes. The Mohican eventually prograded out over the margin to fill graben lows and bury basement highs by the early Middle Jurassic (Wade and MacLean, 1990). The fine muds from this succession were transported by marine processes into deeper water where they slowly infilled basinal lows and blanketed newly formed oceanic crust.

The combination of sea-floor spreading, basin subsidence, and global sea level rise resulted in the Atlantic Ocean becoming broader and deeper (~1000 m) by the Middle Jurassic. A prominent carbonate bank developed in the western part of the basin and persisted until the latest Jurassic-earliest Cretaceous. Tempering the carbonate bank’s growth and extension to the northeast were Upper Jurassic and Lower Cretaceous deltaic successions of the Sable Delta Complex that locally overwhelmed carbonate sedimentation. The carbonate bank succession of the Abenaki Formation is divisible into five members. A carbonate platform and margin succession was initially established along the basin hinge zone (Scatarie Member) and prograded out into deeper waters where marls and clastic muds were deposited. Continuing margin subsidence coupled with global sea level rise resulted in transgression during which time the carbonates and other shelf sediments were blanketed by deeper marine shales (Misaine Member). From the late Middle Jurassic to the earliest Cretaceous, carbonate reef, bank and platform environments formed and thrived along the basin hinge line on the LaHave Platform (Baccaro Member) (Figure 6).

Further north, a shallow mixed carbonate-clastic ramp succession existed on the Banquereau Platform and in deeper water a thin succession of shales and limestones were deposited (DSDP J1 Reflector). Only on the western LaHave Platform distal from deltaic influences did carbonate sedimentation persist into the Early Cretaceous (Artimon and Roseway members).

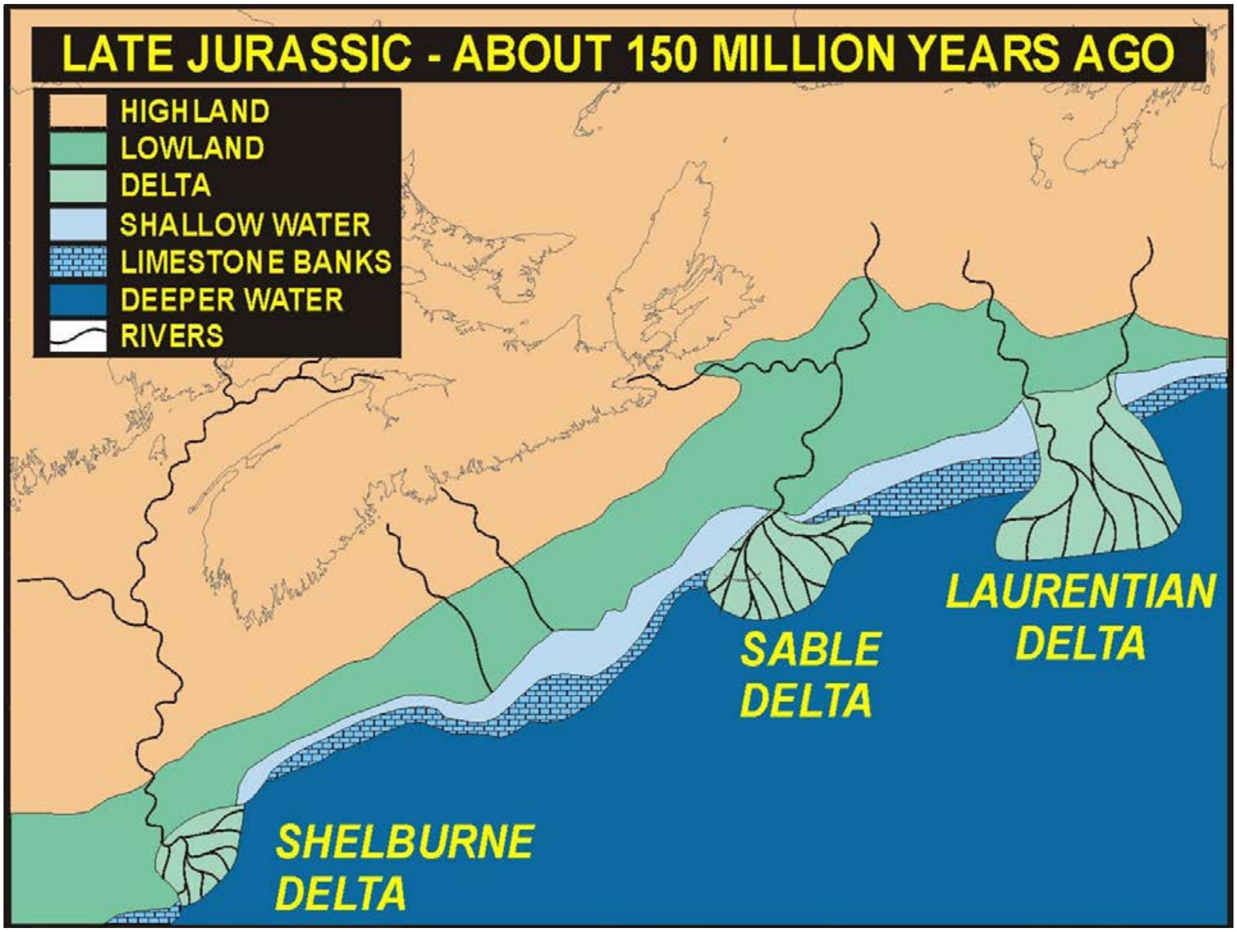


Figure 6. *Simplified paleogeographic reconstruction of the Scotian Basin during the Late Jurassic (~Kimmeridgian) time, ca. 150 Ma. This period represents the final stage of the Abenaki carbonate margin; soon to be overwhelmed by the rapidly advancing Mic Mac Formation siliciclastic delta systems. The margin had a ramp-like morphology between the Sable and Laurentian deltas and developed a more classic fringing reef profile elsewhere. Copyright © Atlantic Geoscience Society – used with permission.*

LATE POSTRIFT

Concurrent with carbonate deposition, regional uplift to the west resulted in an influx of clastic sediments and the establishment of the mixed energy (current and tidal) Sable Delta complex in the Laurentian Subbasin, and slightly later in the Sable Subbasin. In the southwest, a similar progradation occurred at the U.S.-Canada border region and identified as the Shelburne Delta (Wade and MacLean, 1990). These sediments were primarily sourced from the adjacent thick (14+ km) blanket of latest Devonian to Permian sediments centred in the Gulf of St. Lawrence region covering the entire Atlantic Provinces region and parts of New England (Pe-Piper and Piper, 2004; Pe-Piper and MacKay, 2006). The Mic Mac Formation records this first phase of delta progradation into these subbasins, represented by distributary channel and delta front fluvial sands cyclically interfingering with prodelta and shelf marine shales of the Verrill Canyon Formation.

The ancestral St. Lawrence River was firmly established by the earliest Cretaceous, delivering increasing supplies of clastic sediments into the Scotian Basin encroaching and burying adjacent coeval Abenaki Formation carbonate reefs and banks on the LaHave Platform and later the Banquereau Platform. A series of thick sand-rich deltaic, strandplain, carbonate shoal, and shallow marine shelf successions (Missisauga Formation) dominated sedimentation throughout the Early Cretaceous (Figure 7). The Sable Delta prograded rapidly southwest into the Laurentian and Sable subbasins and over the Banquereau Platform, while in the Shelburne Subbasin the Shelburne Delta waned due to the exhaustion of its sediment supply. Along the LaHave Platform, small local rivers draining off the southwest Nova Scotia mainland provided modest amounts of sands and shales to this region and associated deeper water realm.

Middle Jurassic and Cretaceous sediment loading of unstable shelf sediment along and to the south of the basement hinge zone initiated subsidence and development of seaward-dipping growth faults that acted as traps for sand. Sediment loading also mobilized older Argo Formation salts creating a complex slope morphology (e.g. Kidston et al., 2002; Shimeld, 2004) analogous to other basins with mobile salt substrates (e.g. Gulf of Mexico). Continuous sedimentation accentuated salt mobility, and in areas of high sedimentation like the Sable and possibly Shelburne deltas, salt moved both vertically and expelled laterally in the seaward direction forming diapirs, pillows, canopies and related features. During periods of low sea level, extant rivers incised exposed outer shelf sediments, with shelf-edge delta complexes forming at the edge of the continental shelf (Cummings & Arnott, 2005; 2006). Such deltas supplied turbidity currents and other mass transport deposits to the slope during the Middle Jurassic through Cretaceous, where potential reservoirs deposited in canyons and localized withdrawal-related minibasins in the deeper water salt province.

Deltaic sedimentation ceased along much of the Scotian margin following a late Early Cretaceous major marine transgression blanketed the shelf with thick shales of the Naskapi Member of the Logan Canyon Formation. Transgressive successions were interrupted periodically during the influx of coarser clastics in the Aptian-Cenomanian (Cree and Marmora members of the Logan Canyon; Wade and MacLean, 1990). Sand was deposited along a broad coastal plain and shallow shelf system, but eventually gave way as deeper marine shales (and some limestones) of the Dawson Canyon Formation were deposited as sediment supply decreased from the lower relief hinterland. The end of the Cretaceous period in the Scotian Basin experienced basin subsidence, rise in sea level, and deposition of marine marls and chalky mudstones of the Wyandot Formation. Tertiary age marine shelf mudstones, and later shelf sands and conglomerates of the Banquereau Formation buried these strata (Figure 8).

Throughout the Tertiary, several major unconformities related to sea level falls occurred. During Paleocene, Oligocene and Miocene times, fluvial and deep-water current processes cut into, and eroded, mostly unconsolidated sediments and transported them out into the deeper water slope and abyssal plain. During the Quaternary Period of the last 2 million years, several hundred metres of glacial and marine sediments were deposited on the outer shelf and upper slope.

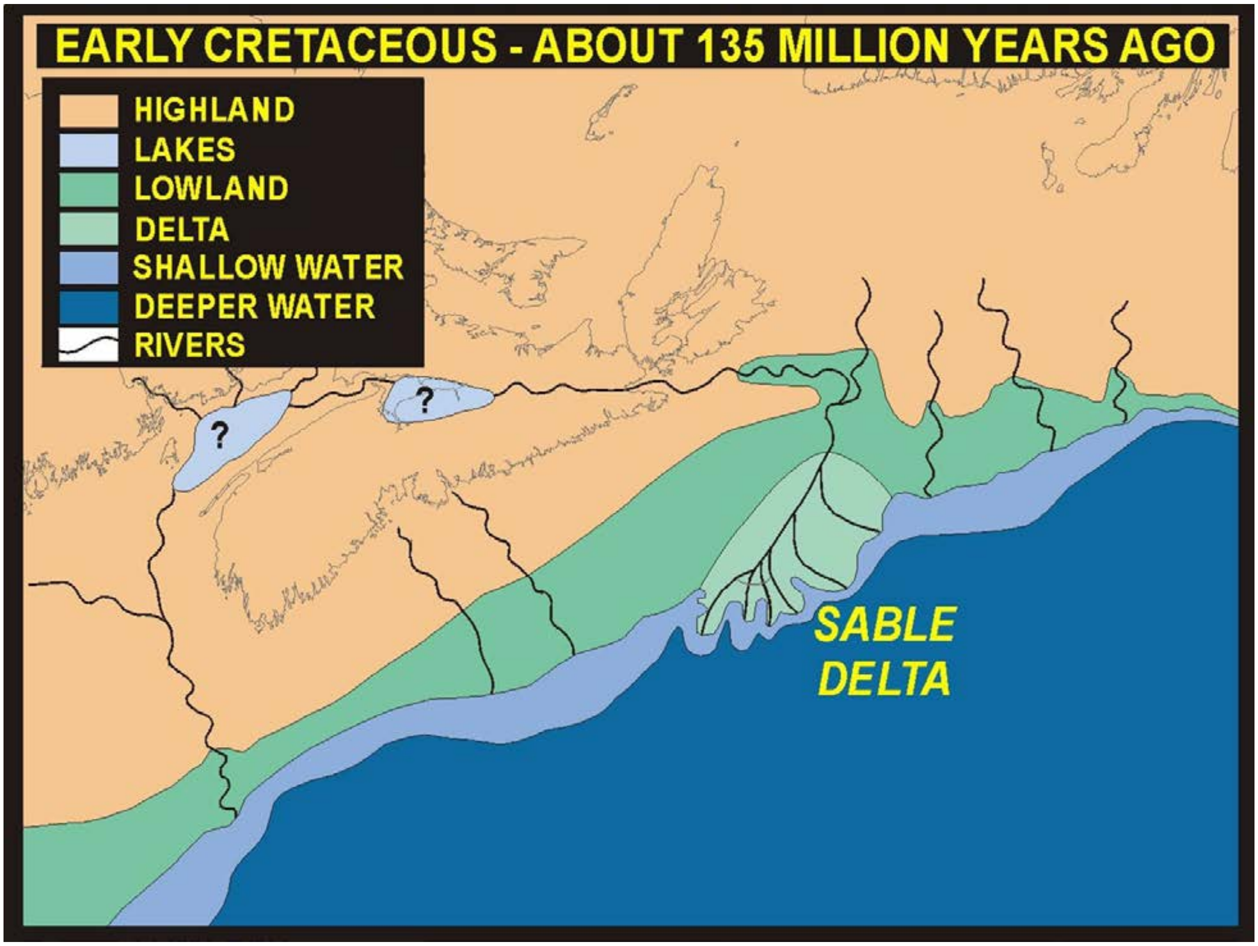


Figure 7. *Simplified paleogeographic reconstruction of the Scotian Basin during the Early Cretaceous (~Valanginian) time, ca. 135 Ma. Deltaic sedimentation in the east was consolidated in the Sable Subbasin, having ceased in the Shelburne Subbasin to the west due to depletion of its sediment sources. The Sable Subbasin's faulted basement and deeply buried salts coupled with rapid sedimentation facilitated the creation of many syndepositional growth-fault structures, thick reservoir sand deposition, and resultant over-pressure conditions. Copyright © Atlantic Geoscience Society – used with permission.*

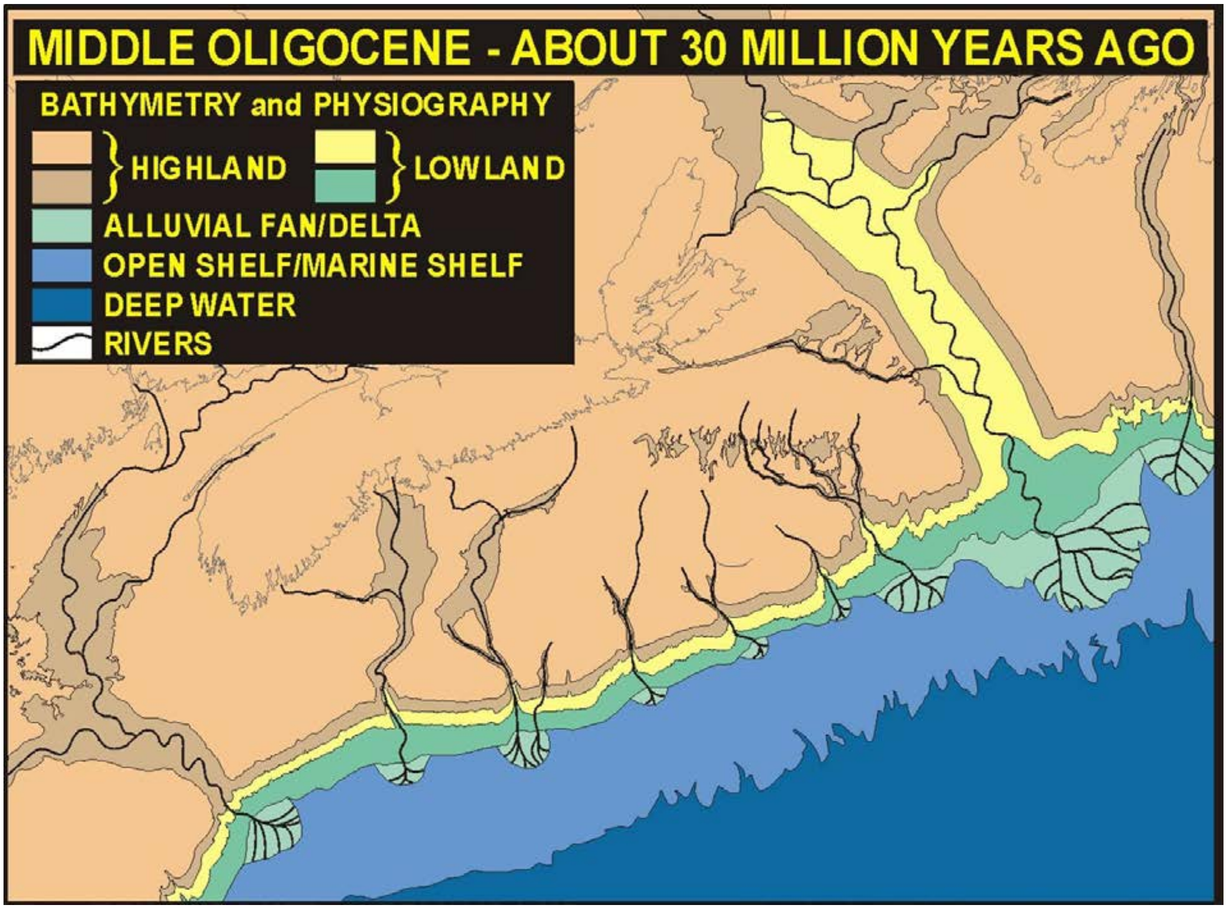


Figure 8. *Simplified paleogeographic reconstruction of the Scotian Basin during the Upper Oligocene (Chattian) ca. 30 Ma. The figure illustrates the Chattian age sea level fall and resultant exposure and erosion on the Nova Scotia margin (Chattian unconformity). Smaller shelf margin deltas and their locations are speculative. Slightly modified after the Atlantic Geoscience Society – Copyright © AGS, used with permission.*

REFERENCES

Brown, D.E., Dehler, S.A., Louden, K. and Yue, W., 2007
The Early Jurassic Heracles Sequence, Scotian Basin, Canada: Recognition of latest stage synrift tectonism and correspondence to structures offshore Morocco.
1st Moroccan Association of Petroleum Geologists International Conference and Exhibition, Marrakech, October 28-31, 2007, Abstracts & Program, p.17-18.
http://www.searchanddiscovery.com/abstracts/pdf/2008/mapg_morocco/abstracts/ndx_brown.pdf

Cummings, D.C. and Arnott, R.W.C., 2005
Growth-faulted shelf-margin deltas: a new (but old) play type, offshore Nova Scotia.
Bulletin of Canadian Petroleum Geology, **53**(3), p.211-236.

Cummings, D.C., Hart, B.S. and Arnott, R.W.C., 2006
Sedimentology and stratigraphy of a thick, areally extensive fluvial-marine transition, Missisauga Formation, offshore Nova Scotia and its correlation with shelf margin and slope strata.
Bulletin of Canadian Petroleum Geology, **54**(2), p.152-174.

Haq, B.U., Hardenbol, J., and Vail, P.R., 1987
Chronology of Fluctuating Sea Levels Since the Triassic.
Science, **235**, p.1156-1167.

Kidston, A.G., Smith, B., Brown, D.E., Makrides, C. and Altheim, B., 2007
Nova Scotia Deep Water Offshore Post-Drill Analysis – 1982-2004.
Canada-Nova Scotia Offshore Petroleum Board, Halifax, Nova Scotia, 181p.
http://www.cnsopb.ns.ca/sites/default/files/pdfs/Deep_Water_Post_Drill_Analysis_2007.pdf

Kidston, A.G., Brown, D.E., Smith B.M. and Altheim, B., 2002
Hydrocarbon Potential of the Deep-Water Scotian Slope.
Canada-Nova Scotia Offshore Petroleum Board, Halifax, 111p.
http://www.cnsopb.ns.ca/sites/default/files/pdfs/Hydrocarbon_Potential_Scotian_Slope.pdf

Pe-Piper, G. and MacKay, R.M., 2006
The Provenance of Lower Cretaceous sandstones onshore and offshore Nova Scotia from electron microprobe geochronology and chemical variations of detrital monazite.
Bulletin of Canadian Petroleum Geology, **54**(4), p.366-379.

Pe-Piper, G. and Piper, D.J.W, 2004
The effects of strike-slip motion along the Cobequid-Chedabucto-southwest Grand Banks fault system on the Cretaceous-Tertiary evolution of Atlantic Canada.
Canadian Journal of Earth Sciences, **41**(7), p.799-808.

Schenk, P.E., 1997
Sequence stratigraphy and provenance on Gondwana's margin: the Meguma Zone (Cambrian to Devonian) of Nova Scotia, Canada.
Geological Society of America Bulletin, **109**(4), p.395-409.

Shimeld, J., 2004
A comparison of salt tectonic subprovinces beneath the Scotian Slope and Laurentian Fan.
In: P.J. Post, D.L. Olsen, K.T. Lyons, S.L. Palmes, P.F. Harrison, and N.C. Rosen (eds), Salt-*Sediment Interactions and Hydrocarbon Prospectivity: Concepts, Applications, and Case Studies for the 21st Century*, 24th Annual GCS-SEPM Foundation Bob F. Perkins Research Conference, Houston, p.502-532, CD-ROM.

Wade, J.A. and MacLean, B.C., 1990
Chapter 5 - The geology of the southeastern margin of Canada, Part 2: Aspects of the geology of the Scotian Basin from recent seismic and well data.
In: M.J. Keen and G.L. Williams (eds), *Geology of Canada No.2 - Geology of the continental margin of eastern Canada.* Geological Survey of Canada, p.190-238 (also Geological Society of America, *The Geology of North America, Vol.I-1*).

Wade, J.A., Brown, D.E., Fensome, R.A. and Traverse, A., 1996
The Triassic-Jurassic Fundy Basin, Eastern Canada: regional setting, stratigraphy and hydrocarbon potential.
Atlantic Geology, **32**(3), p.189-231.

Welsink, H.J., Dwyer, J.D. and Knight, R.J., 1990
Tectono-Stratigraphy of Passive Margin off Nova Scotia.
In: A.J. Tankard and J.R. Balkwill (eds), *Extensional Tectonics and Stratigraphy of the North Atlantic Margins.* American Association of Petroleum Geologists, Memoir 31, p.215-231.