Lacustrine source rock potential in the Middle Triassic – Early Jurassic Chignecto Subbasin, offshore Eastern Canada

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PREAMBLE: *This document is a significantly modified, revised and expanded version of the oral presentation given at the Geological Association of Canada / Mineralogical Association of Canada Annual Meeting, University of New Brunswick, Fredericton, New Brunswick, May 21-23, 2014. It is a high level overview of possible scenarios for the development of source rock successions within the Fundy Basin, and by extension, the offshore southwest Scotian Basin.*

The original hypothesis was that the older the Late Triassic rift basin strata, the further south in latitude it was deposited. That in turn would elevate the probability of source rock development of those basins that were located in the equatorial tropical zone. However, climate is not the only influencing factor in controlling precipitation / evaporation and sediment input. Tectonism plays an equally important role through the creation of basin accommodation space via subsidence. It is the interplay of these factors that determines the type of the lake basin created and its internal stratigraphic architecture, and most importantly, the physical and chemical properties of related source rock facies. New data (specifically seismic) is required to image Late Triassic synrift, pre-salt basins and define potential internal source rock facies in the Scotian Basin and its environs.

ABSTRACT

Recent discoveries of super-giant, multi-billion barrel pre-salt oil fields in Brazil's offshore basins and related discoveries in its African conjugates have highlighted the great importance of synrift / pre-breakup fluvial-lacustrine successions to the success and efficiency of their petroleum systems. Improvements in seismic acquisition and processing technologies were keys in imaging the architecture of the underlying rift basins, and interpreting the basin fill and internal depositional facies later confirmed by drilling.

Middle Triassic to Early Jurassic synrift basins are exposed onshore eastern North America (Newark Supergroup) and extend into adjacent offshore areas with equivalent basins in Northwest Africa. Organic-rich lacustrine successions occur in a number of the U.S. basins and although no commercial discoveries have been made, hydrocarbon shows in outcrops and a few wells confirmed that a working petroleum system existed. The basin-fill model for these extensional basins' sedimentary successions defines four tectonostratigraphic (TS) units. TS I is an unconformity-bounded, early synrift fluvial-eolian sequence of Late Permian age. TS II is a dominantly fluvial (with some lacustrine) sequence believed representative of an underfilled, hydrologically-open basin (subsidence < sedimentation). This is followed by either a closed basin or one in hydrological equilibrium (subsidence ≥ sedimentation) dominated by lacustrine (TS III), and later playa / lacustrine (and basal CAMP volcanics) successions (TS IV). The climate sensitive lacustrine facies - especially in TS III - are exquisite recorders of paleoclimate, and with paleomagnetic data refine the determination of the basins' paleo-latitudinal positions.

Seismic profiles in the Fundy-Chignecto (Canada) and Newark (USA) basins reveal high amplitude, laterally continuous reflections adjacent to the respective boarder faults in both TS II and TS III. In the former, they are distal to updip fluvial successions and are interpreted as large, laterally equivalent deep-water lacustrine facies. This architecture departs from the TS model by inferring high levels of tectonically-driven extension / subsidence and a hydrologically open basin. The seismic reflection character of interpreted fluvial and lacustrine successions mirrors facies associations that correspond to deposition in hydrologically open, overfilled (subsidence ≤ sedimentation) and hydrologically open and closed, balanced filled (subsidence ≈ sedimentation) lake basin types.

During TS II deposition (approximately Late Anisian to Early Carnian), paleomagnetic data positions these basins within the north equatorial humid belt and over time drifted towards the semiarid subtropical climate zone. Seismic data is interpreted to reveal these basins as representative of overfilled and balanced filled lake basin types. Together, this combination suggests that a favourable setting existed for the creation of source rock intervals. Therefore, a potential new oil-rich resource play may exist within the faulted and fractured lacustrine successions of the Wolfville and Blomidon formations beneath the shallow waters of Chignecto Bay.

Though recognizing that profound differences in water input, subsidence and resultant stratal successions can exist in adjacent and/or linked lakes, this interpretation would also have a significant impact on the potential for source rocks in Late Triassic lacustrine successions in pre-salt synrift basins offshore Nova Scotia and Morocco.

FIGURE COMMENTARIES

Figure 1: TITLE Slide.

Figure 2: Distribution of Middle Triassic to Early Jurassic Newark Supergroup synrift basins at earliest Jurassic (Hettangian) time, post-CAMP emplacement. The sedimentary infill successions of the three highlighted basins – Richmond, Newark and Fundy – will be discussed and compared as they have been influenced by their paleogeographic position and resultant climate over time. Note the position of the basins in relation to the paleo-equator and northern latitude lines, with the centre of the Fundy Basin at ~15°N paleolatitude (13-16° range) at this time. Blue lines define the humid tropical belt; red lines the semi-arid to arid tropical belt. Modified after Olsen and Et-Touhami (2008).

Figure 3: Satellite image of the Bay of Fundy region showing the basin outline (brown), main faults (red), and four subbasins (Fundy, Grand Manan, Chignecto and Minas) that constitute the Fundy Basin complex. Definition of the southwestern extent of the Fundy Basin into the Gulf of Maine is imprecise being based on shallow sparker data that reveals reflection geometries interpreted as Triassic age sediments. The shallow penetration (<1.0 seconds TWTT) does not permit clear determination of the successions' thicknesses (Ballard and Uchupi, 1975). Two wells have been drilled in the basin: Mobil-Gulf Chinampas N-37 (1975; 3661m TD in sandstones of the Carnian Wolfville Fm.), and the Irving-Chevron Cape Spencer No.1 (1983; 2587m TD in early Paleozoic metavolcanics). No hydrocarbons were encountered in either well that were drilled to test large (?)Middle Jurassic age extensional (N-37) and compressional (No.1) anticlinal structures respectively (Wade *et al.*, 1996).

Figure 4: Model of basin fill successions – Tectonostratigraphic units (TS) – within the Newark Supergroup basins and NW African equivalents as defined by Olsen (1997), and Olsen and Et-Touhami (2008). All TS units are separated by unconformities / hiatus, though it is acknowledged that these boundaries are likely conformable in the basin depocentre. TS I is composed of fluvial-eolian strata and based on paleomagnetics, stratigraphic position and limited biostratigraphic control, and is dated as Late Permian. TS II is fluvial-dominated though with interpreted extensive lacustrine facies in the basin centre as presented in this paper. TS III is a lacustrine-playa succession, and TS IV has CAMP extrusive volcanics at its base (Rhaetian / latest Triassic) followed by playa, fluvial, eolian and

other facies into the Early Jurassic (Hettangian - ?). Potential source rock successions (SR) are known in the TS III and IV units of the US basins (Pratt *et al.*, 1985), and TS II interpreted in this presentation to be present in the Newark and Fundy basins, and possibly in other northern basins. Note that the colour code for the respective TS units I-IV and their associated stratigraphic units (red-green-blue-yellow respectively) will be followed throughout the presentation.

Figure 5: Nomogram of time and geography for the Newark Supergroup, eastern North America illustrating the response of sedimentation over climatic zones though time and northward plate movement (Olsen *et al.* 2000). During the Carnian, climate-sensitive lacustrine facies (Olsen and Kent 1996) and faunal distributions (Whiteside *et al.* 2011) infer a narrow equatorial humid belt about 6° wide centred on the paleoequator. Geomagnetic modelling by Kent and Tauxe (2005) however suggest that this zone was broader and more comparable to today's ~10° humid monsoonal tropical belt (blue lines), with subsequent research as summarized by Preto *et al.* (2010) supporting this interpretation. In the Richmond, Newark and Fundy-Chignecto basins, TS II and III lacustrine intervals are identified by the light blue and light green bars, with dark blue and dark green identifying known deep-water lacustrine facies respectively. Though not highlighted with a green coloured bar, lacustrine strata are recognized in the equivalent TS II succession of the Moroccan Argana Basin. Slightly modified after Olsen *et al.* (2000).

Figure 6: Comparison of the key components and elements of the lacustrine depositional models created by Olsen and Bohacs and their fellow collaborators: Olsen (1990), Olsen and Kent (2000), Olsen and Et-Touhami (2008), Carrol and Bohacs (1999), Bohacs et al. (2002), Bohacs (2012). Note that Olsen's models are restricted to the lacustrine successions in the Newark Supergroup and related basins and except for the older (Carnian) Richmond Type are Norian in age (i.e. his Tectonostratigraphic unit III). Pointedly, they do not include lacustrine facies laterally equivalent to known fluvial successions interpreted by this author to exist in Carnian TS II successions within the Newark and Fundy-Chignecto basins.

Figure 7: Summary of the lacustrine complex styles for the Fundy, Newark and Richmond type basins with approximate latitudinal ranges as defined by Olsen (1997). Limited seismic data (Richmond type; Cornet and Olsen, 1990) has been included to define these lacustrine styles. The respective latitudinal positions are interpreted to determine the climate and resultant facies development which changes in response to northward continent drift (humid tropical to semi-arid to arid). Note that the Richmond type complex is within the older TS II interval (Carnian), with the remainder all in the Norian. The following slides will examine these complexes from the equatorial region northwards. Modified after Olsen (1997), and Olsen and Et-Touhami (2008).

Figure 8: Actual representative outcrop sections of individual transgressive-regressive van Houton lacustrine cycles from synrift continental basins of eastern North America (Olsen, 1986; 1990) and Greenland (Olsen and Kent, 2000). These represent Milankovitch precessional cycles that are interpreted to record the influence of latitudinal position and climate on cyclic lacustrine deposition, with the equatorial basins recording ~10 ky cycles whereas those north and south of the equator reveal ~20 ky cycles (Olsen and Kent 2000; Olsen and Et-Touhami 2008). Thicknesses of the respective sections are shown in blue. Based on limited geochemical data (see compilation in **Figure 34**), intervals having the highest organic content (and hence potential source rocks) are indicated by the red diamonds that correspond to highstand (deep water) black shale intervals. As a result of the northward drift of Pangea, the climate reflecting the paleolatitudinal position of the Newark Supergroup basins had a broad influence on their facies development and lithologies, particularly the lacustrine successions of TS III and IV (and TS II as interpreted by this author – see below). Through time, the southern basins transited across the paleoequator and remained in the humid tropics whereas basins to the north moved from the humid tropics, through the arid belt, and then into the drier subtropical and temperate regions. Modified after Olsen and Et-Touhami (2008).

Figure 9: Location of the Richmond Basin in the early Carnian (~232 Ma) based on the nomogram of Olsen *et al.* (2000) (**Figure 5**). Note the position of the equator and the basin's ~4°S paleolatitude location placing it within the

humid tropical climate zone (blue lines) at that time. The yellow star denotes the approximate relative age in the time scale bar. Modified after Olsen (1997).

Figure 10: Details of the facies model for the TS II Richmond type lacustrine complexes based on outcrop, borehole, well and limited seismic data (Olsen, 1990; 1997; Cornet and Olsen, 1990). The depositional sequences are dominated by stacked progradational successions of fluvial and deep-water lacustrine facies associations with common coals (lowstand) and black shales (highstand). These lacustrine successions are documented to be the thickest as indicated in **Figure 8**.

Figure 11: Location of the Newark Basin in the Early Norian (~219 Ma). Note the position of the equator and the basin's ~6°N paleolatitude placing it in the transition from humid to semi-arid tropical climate zone transiting to the north over time. Modified after Olsen (1997).

Figure 12: Details of the facies model for the TS III Newark type lacustrine complexes based on well and borehole data (Olsen, 1997). The depositional sequences are dominated by stacked progradational and aggradational successions of fluvial and lacustrine facies associations. The lacustrine facies show repeated expansion and contraction reflecting pronounced climatic-induced cyclicity (~20 ky 'Van Houten' Milankovitch precession cycles). Highstand deep water shales have elevated TOCs (Pratt et al., 1986).

Figure 13: Location of the Fundy Basin in the Late Norian (~210 Ma). Note the position of the equator and the ~12°N paleolatitude of the basin centre placing it within the arid climate zone and transiting to the north over time. Modified after Olsen (1997).

Figure 14: Details of the facies model for the TS III Fundy type lacustrine complexes based on outcrop, borehole and well data (Olsen, 1997). The depositional sequences are dominated by thin, evaporitic aggradational successions of playa, lacustrine and eolian facies associations. Similar to the Newark type successions, high climatic cyclicity is recorded in these strata of alternating wet (lacustrine) and dry (playa) cycles. However, it is important to note that the Fundy type model is based on examination of Blomidon Formation onlap strata only on the up-dip basin margin edge. Significantly, seismic data reveals that it is about 3000 metres thick in the centre of the Fundy Basin (Wade *et al.*, 1996), and thus this model significantly understates the potential for longer lived, perennial lakes in the basin centre. Indeed, the basin's 10 km+ of strata reveals it had a significant amount of extension over the same period of equivalent formations in other related basins inferring that tectonically driven subsidence had a profound impact on basin fill and facies development.

Figure 15: The Bohacs lacustrine basin model reflects the balance between basin accommodation tectonic-driven subsidence / accommodation and climate-driven sediment input and water supply. Three end member lacustrine basin types are recognized with associated facies associations. Modified after Carroll and Bohacs, (1999).

Figure 16: Schematic diagram of lake basin types as controlled / influenced by tectonic-driven accommodation and climate-driven water and sediment input. The overfilled lake basin reflects the dynamic of potential basin accommodation being less than the rate of water and sediment input such that water inflow and outflow is balanced and results in the creation of fluvial-lacustrine facies associations. In balanced filled lake basins, accommodation / subsidence and water and sediment input are approximately equal forming fluvial-lacustrine and migrating lake margin facies (fluctuation profundal). Underfilled lake basins record settings where accommodation / subsidence is greater than water and sediment input. Here, evaporation plays a greater role and results in a dominantly lacustrine-playa facies association with associated evaporites. Modified after Carroll and Bohacs, (1999), and Bohacs *et al.,* (2002).

Figure 17: Summary of the lacustrine facies associations associated with overfilled, balanced filled and underfilled lake basin types (Carroll and Bohacs, 1999; Bohacs et al., 2000; Bohacs, 2012). Details on each are described in the following figures. Modified after Bohacs (2012).

Figure 18: Details on the overfilled basin fluvial-lacustrine facies association (Bohacs *et al.*, 2002; Bohacs, 2012). The stratal fill is dominated by mostly progradational parasequences of fluvial-deltaic sandstones and lake margin to deep water lacustrine shales. These strata were deposited in an open hydrology (fresh water) setting with water and sediments sourced from perennial river systems. Coals and marginal bioclastic shoals can also be developed. This stratigraphy is similar to Olsen's (1990) Richmond type lacustrine basin model based on the Vinta Member (**Figure 10**). These lake sediments have low to moderate levels of TOC composed of Types I-III kerogens.

Figure 19: Details on the balanced filled lake basin fluctuating profundal facies association (Bohacs *et al.*, 2002; Bohacs, 2012). The mixed progradational and aggradational parasequences record periods of mixed progradation and desiccation of fluvial sandstones and lacustrine shales and mudstones, with considerable lateral migration of lake margin facies. These successions are highly cyclic and record deposition in lake basins with alternation open and closed hydrologies with respective fresh-alkaline-saline waters. This stratigraphy is similar to Olsen's (1990) Newark type lacustrine basin model based on the Lockatong Formation where periods of desiccation extended across the entire basin (**Figure 12**). These lake sediments have moderate to high levels of TOC composed of Type I kerogens.

Figure 20: Details on the underfilled basin evaporative facies association (Bohacs *et al.*, 2002; Bohacs, 2012). The parasequences recorded in these basins are dominantly aggradational with much reduced input of fluvially-derived water and sediments and high rates of evaporation. These highly cyclic, dominantly lacustrine-playa (wet-dry) parasequences display aggradational stacking patterns and were deposited is a closed basin setting with saline to hypersaline lake waters. Fluvial input is much reduced and expressions of these ephemeral braided fluvial systems and eolian limited to the basin margins. This stratigraphy is similar to Olsen's (1990) Fundy type lacustrine basin model based on the Blomidon Formation (**Figure 14**). These lake sediments have low to high levels of TOC composed of Type I kerogens.

Figure 21: Geological map of the Newark Basin with TS units and associated colour code indicated in the legend. Note the fault-bounded subbasins that comprise the Newark Basin complex. The location of the Norpac NB-1 seismic line is indicated in red and shown in **Figure 22**. Modified from Withjack *et al.* (2013).

Figure 22: Newark basin seismic line Norpac NB-1. High amplitude, laterally-continuous reflections correlate to the TS III lacustrine Lockatong Formation. Near-identical reflections are present in the underlying, down-dip equivalent of the Stockton Formation ("Stockton Lacustrine") and deeper "Buried Stockton". These TS II successions have not been penetrated except the former near the basin-bounding fault where lacustrine sediments are present in the NCO Cabot KBI No.1 well (Withjack *et al.*, 2013) and the Princeton cores of the Newark Basin Coring Project (Olsen *et al.*, 1996). Seismic interpretation modified from Withjack *et al.* (2013). Seismic line from Bally *et al.* (1990).

Figure 23: Enlargement of the Norpac NB-1 seismic line over the basin depocentre. The Lockatong Formation lacustrine succession reflections are interpreted to represent individual ~400 ky cycles (Reynolds and Olsen, 1994). As noted previously, similar reflections in the underlying Stockton Formation have yet to be penetrated to confirm interpreted deep water lacustrine facies as well as for the underlying "Buried Stockton". Source rocks (SR) are known in the Lockatong Formation and similar strata in other basins, but data is difficult to obtain. What is available reveals that within the Lockatong TOCs range from 1-3.5% (Pratt *et al.*; 1985, Olsen, 1985; Pratt *et al.*, 1986; Schultz *et al.*, 1988).

Based on Olsen's (1990) model, the equatorial paleolatitudinal position of the interpreted Stockton lacustrine successions ("SL" and "SB") would be expected to have Richmond-type lacustrine sequences with similar TOCs. Similar sequences could exist in the unknown "Buried Stockton". Though of only fair quality, the seismic reflections show some evidence of low angle downlap and linked high amplitude, laterally-continuous reflections suggesting progradational fluvial strata advancing into a lake setting. This pattern could be interpreted as reflecting deposition in a balanced filled lake basin with deposition ≈ subsidence (Bohacs, 2002).

Figure 24: Stratigraphy of the Fundy Basin. Onshore thicknesses are from various authors; those offshore from Wade *et al.* (1996). The 201.7 My age of the North Mountain CAMP basalt is from the compilation in Blackburn *et al.* (2013). The upper age of the McCoy Brook formation is unknown though Wade *et al.* (ibid) estimate that it could be as young as Aalenian. Outcrop photos represent successions along the fault margin, or upper edge of the basins' ramp margin. Thicknesses are much greater in the basins' depocentres as well as facies being significantly different than their marginal equivalents (Wade *et al.*, ibid). Lithology column via P.E. Olsen: McCoy Brook = fluvial and lacustrine mudstones and sandstones; North Mountain = tholeiitic basalts; Blomidon = playa-lacustrine shales and mudstones, basal eolian sandstones; Wolfville = braided fluvial sandstones; Carrs Brook = fluvial sandstones and overbank mudstones; Honeycomb Point = braided fluvial and eolian sandstones, minor mudstones. Time scale V2014/02 from ICS (2014).

Figure 25: Depth structure map of the North Mountain Formation, Fundy Basin. The location of the seismic lines 82-29 and BF-72 are labelled and shown in red; the thick lines represent the line portions shown in the following figures. Note that the Chignecto Subbasin's southern boundary is fault-bounded (east-west trending Cobequid-Glooscap-Chedabucto strike-slip fault) with both extensional and compressional features along its margin. The St. Martin's and Martin Head outcrop sections (Wolfville Fm. equivalent) are labeled "SM" and "MH" respectively. Map scale identical to that for the Newark Basin (**Figure 21**).

Figure 26: Central segment of seismic line BF-72, Fundy Basin. This line extends across the main Fundy Basin depocentre and intersects the Mobil-Gulf Chinampas N-37 well near the northwest end of the line (not shown). Based on the well's velocity survey, about 10 km of Middle Triassic to Middle Jurassic are present. The CAMP tholeiitic basalts of the North Mountain Formation (NMB) are clearly visible and are about 1 km thick. The seismic character of the overlying McCoy Brook strata shows a number of laterally continuous reflections representative of playa-lacustrine successions observed in wells and onshore. The NMB has affected the response and resolution of reflections in the underlying Blomidon and Wolfville formations. The latter displays a number of moderate to high amplitude laterally-continuous reflections interpreted to represent lacustrine strata, though their clarity is affected by the NMB and sea bed multiples. The poor data quality beneath the Wolfville makes interpretation difficult, and was originally interpreted by Brown (1986, 1986a) and Wade *et al.* (1996) to represent Cambro-Ordovician metasediments of the Meguma Terrane. Alternatively, this succession could be representative of the Late Permian TS I. The Fundy Decollement (Brown, 1986, 1986a; Keen *et al.*, 1991; Wade *et al.*, 1996) is the horizontal plane of the vertical Cobequid- Glooscap-Chedabucto strike-slip fault upon which the Meguma overthrusted the inboard Avalon Composite Terrance in the Permo-Carboniferous. It was reactivated through extension related to Pangean break-up to the east in the Middle Triassic with motion extending well into the Middle Jurassic.

Figure 27: Seismic line 82-29, Chignecto Subbasin with three of the four TS units (II-IV) present. High amplitude laterally-continuous reflections are present in the basin depocentre and down-dip portions of TS II (Wolfville) and III (Blomidon) that are interpreted to be lacustrine successions ("WL" and "BL"). Their estimated aerial extent is approximately 400 km^2 with a combined maximum thickness of about 2700 m (estimate derived from the Chinampas N-37 well velocity survey). The basin strata have undergone a significant extensional episode sometime in the Early to Middle Jurassic that have attenuated, faulted and fractured the lacustrine sediments to varying degrees. This is indicated by the faulting extending into the Hettangian and younger McCoy Brook Formation. The

positive flower structure to the east is a locking bend of the sinistral Cobequid-Glooscap-Chedabucto strike-slip fault.

Within the Chignecto Subbasin, the Wolfville succession rests unconformably on interpreted Alleghenian-age thrust faults that involve Carboniferous (Namurian-Westphalian) coal measures of the Cumberland Group. These rocks are exposed in continuous section along the southeast coast of Chignecto Bay, Nova Scotia to the northeast. Onshore at Martin Head, New Brunswick and about 5 km northeast of the end of line ('MH" in **Figure 25**) are exposed Wolfville Formation equivalent red to tan fining-upward fluvial sandstones with common wood and plant remains. Pollen and spores indicate a Middle Carnian age (data supplied by this author to Olsen and Et-Touhami, 2008 and tabulated therein). Black boxes illustrate the enlarged, detailed sections of the line in the next two figures (**Figures 28 & 29**).

Figure 28: Enlargement of the central ("C") portion of line 82-29, Chignecto Subbasin as indicated in **Figure 27**. Onlap is observed in the basal portion of the Wolfville Formation (TS II) on to the rift onset unconformity with underlying thrust slices of the Late Paleozoic coal measures observed onshore Nova Scotia (Cumberland Basin). Interpreted channels and downlapping seismic signatures are consistent with the architectures defining lacustrine deposition in overfilled and balanced filled lake basins (Bohacs *et al.*, 2000, 2002; Bohacs, 2012). The reflection defined with a dashed line within the Wolfville Formation / TS II interval could represent the Carnian Pluvial Event (CPE) (see Petro *et al.* (2010) and listed citations therein).

Figure 29: Enlargement of the western ("W") portion of line 82-29, Chignecto Subbasin as indicated in **Figure 27**. The extent of the succession's faulting plus lack of growth in hanging wall blocks suggests that the event was probably late Early to early Middle Jurassic in age, assuming a latter age for the top of the McCoy Brook succession (Wade *et al*., 1996). Wolfville strata reveal significant amounts of attenuation and tectonism, with more competence shown in the overlying Blomidon fault blocks. Assuming that source rock facies exist within the lacustrine strata of TS II (green; Wolfville Formation) and III (blue; Blomidon Formation), their subjection to tectonism would create fracture-based porosity and permeability. Within the Blomidon, deep water turbidite sands could be present and sourced from the adjacent (~2 km distant) fault-bounded massif of the late Proterozoic-early Paleozoic Caledonia (Avalon) terrane. Top seal would be provided by the TS IV playa-lacustrine mudstones of the McCoy Brook Formation (M) and tholeiitic basalts of the North Mountain Formation (N). The resultant structures and highly fractured potential source rocks could represent a highly attractive resource play in the shallow (20-40 m) waters of Chignecto Bay.

Figure 30: Interpreted basin type and facies associations for the Carnian Wolfville Formation, Chignecto Subbasin based on seismic, well and outcrop data. Information on the braided fluvial facies is well constrained with excellent outcrop exposures (though are along the margin of the basin hingeline) and well and borehole data. The lacustrine facies is only interpreted through seismic data and has not been drilled. The Wolfville / TS II is interpreted to have been deposited in an overfilled and later balanced filled lacustrine basin with resultant fluvial-lacustrine to fluctuating profundal facies associations (Bohacs 2012). These facies associations are approximately equivalent to the Richmond type and Newark type lacustrine complexes as defined by Olsen (1990).

Figure 31: Schematic diagram of lake types and facies associations as controlled / influenced by tectonic-driven accommodation and climate-driven water and sediment input (Carroll and Bohacs, 1990; Bohacs et al. 2002). The blue dashed line indicates the track of Wolfville Formation / TS II deposition in the Chignecto Subbasin throughout the Carnian. Initial deposition was fluvial followed by increased subsidence and water supply in an overfilled basin setting reflected in a mixed fluvial-lacustrine facies association (Richmond type of Olsen, 1990). Over time, subsidence increased resulting in a balanced filled basin with associated fluctuating profundal facies association (Newark type of Olsen, 1990). Seismic reflection character in the overlying Norian Blomidon Formation / TS III suggests more permanent lakes existed in the early phase of deposition. At the start of deposition (green dashed

line), the basin was still under balanced filled conditions. Over time, water influx was reduced with evaporative lacustrine-playa sedimentation indicative of an underfilled lake basin (Fundy type of Olsen, 1990).

Figure 32: Updated nomogram of time and geography with depositional facies and magnetostratigraphy for the Newark Supergroup, eastern North America illustrating the response of sedimentation over climatic zones though time and northward plate movement (Olsen *et al.,* 2010). Deposition of the Lockatong Formation lacustrine succession occurred between 4-6°N paleolatitude at the margin of the humid tropical zone. Interpreted lacustrine successions from seismic data for the fluvial-dominated Stockton and Wolfville formations are shown in grey, with the former straddling the humid tropical equatorial zone (2°S-4°N), and the latter the humid tropics to the middle of the humid-arid transition zone (3-8°N). Well information from the Newark Basin (NCO Cabot KBI No.1; **Figures 21-23**) reveals the presence of lacustrine facies within the top of the Stockton adjacent to the basin-bounding fault (Withjack *et al.,* 2013). The boundary of TS II and III has thus been adjusted upwards into the Norian to account for the Stockton Formation red lacustrine strata in the Newark Basin.

Note also that lacustrine strata are recognized in the equivalent tectonostratigraphic (TS) II succession of the proximal Argana Basin of Morocco (Hofmann *et al.,* 2000). Based on paleomagnetic data and lake basin type interpretations, the paleolatitudinal positions for the Fundy and Newark basins' TS II units in Carnian time are within or very proximal to the humid tropics where conditions are suitable for the creation of organic material and potential source rocks. Deposition of the TS III Blomidon Formation occurs from ~8-15°N paleolatitude in the humid-arid transition to well into the arid climatic zone. Well and seismic data indicate there is at least 3000 metres of post-CAMP TS IV and post-rift strata remaining in the Fundy Basin (McCoy Brook Formation; far right) which is much greater than originally interpreted by Olsen (Wade *et al.,* 1996). The thickness of material eroded since the Middle Jurassic is estimated to be about 2 km (Wade *et al.,* ibid).

During the Carnian, climate-sensitive lacustrine facies (Olsen and Kent, 1996) and faunal distributions (Whiteside *et al.,* 2011) infer a narrow equatorial humid belt about 6° wide centred on the paleoequator. Kent and Tauxe (2005) suggest that this zone was broader and more comparable to today's humid belt of about 10°. Increasingly arid conditions dominated north and south of this region (5-20°) (**Figures 8 & 9**). During the Late Triassic, lacustrine sediments of the Norian Lockatong Formation ('L') were deposited in semi-tropical conditions. Similar successions are proposed for the older (Anisian-Carnian) Wolfville Formation ('W') when the Fundy-Chignecto Basin occupied the same 6°-8°N paleolatitudinal position (i.e. reversing the ~10° northward drift over the Late Triassic). The Newark Basin would shift southwards into the equatorial humid zone and Stockton lacustrine successions presumably would be similar to Richmond-Newark and/or Richmond cycles defined by Olsen and Kent (2000) (see **Figures 7 & 8**). **Figures 38-40** illustrate and expand these points for the Fundy-Chignecto Basin successions from the map perspective.

Time scale and age of Triassic-Jurassic boundary is from ICS (2014). Age of CAMP basalts / event is from information presented in Blackburn *et al.* (2013). Astronomically-calibrated Geomagnetic Polarity Time Scale (GPTS) from Olsen and Kent (1999). Figure revised and modified after Olsen *et al.* (2010).

Figure 33: Comparison of seismic profiles from the Fundy-Chignecto and Newark basins reveals the gentle expansion of the respective TS units toward the basin-bounding faults (slightly greater in the Chignecto Subbasin). There is an obvious remarkable similarity in basin architecture and seismic response of the internal tectonostratigraphic units (TS II-III). In both basins, high amplitude, laterally continuous reflections in the deepest part of the basins are clearly visible in the respective TS III units (red oval). Note that similar, if not better defined reflections, are seen in the underlying TS II strata that are distal to the fluvial-dominated sediments observed in outcrop on the ramp margin (SE). In the Newark Basin, the NCO Cabot KBI No.1 well penetrated lacustrine sediments near TD (3197 m) in the Stockton Formation (Olsen *et al.,* 1996; Olsen, 2010, Withjack et al., 2013).

Within the Chignecto Subbasin, in addition to a highly fractured lacustrine succession play (**Figure 24**), another could be created through the migration of gas sourced from Late Paleozoic coal measures (yellow arrows) laterally into overlying Triassic fluvial successions (Wolfville Formation). Though no commercial production has occurred, the Pennsylvanian succession in the Cumberland Basin onshore Nova Scotia (Cumberland Group) is historically known to have gas occurrences. A number of studies have assessed its CBM resource potential (*e.g.* Sproule Associates Limited, 2005), and other research has confirmed the potential for gas and liquid hydrocarbons (Mukhopadhyay *et al.*, 1991; 1993).

Correlative TS formations are coloured the same for each basin and in all related figures; the red horizon is the rift-onset unconformity. For simplification, the Boonton Formation includes other related Early Jurassic formations and tholeiitic volcanic units (see **Figure 15**). Vertical and horizontal scales are identical. Interpretations for the NB-1 seismic line are modified after Withjack *et al.* (2013).

Figure 34: Summary of source rock potential of formations within Newark Supergroup basins in the United States from various sources as noted. Generally, there is little published geochemical data on their potential source rock successions that is further compounded by limited access to well information and overlapping government jurisdictions. Nevertheless, this table provides an insight on the sedimentary units that have organic-rich intervals and source rock potential.

Figure 35: Time-structure map of the top allochthonous Argo Formation salt of Rhaetian-Hettangian age on the southwest half of the Scotian Basin (Deptuck, 2011). The Mohawk, Mohican and Naskapi graben complexes are inboard of the basin hingeline on the shallow water LaHave Platform and are part of the Newark Supergroup. Only within the Mohican Graben are bedded salts and CAMP tholeiitic basalts as confirmed by the Mohican I-100 and Glooscap C-63 wells. The location of the seismic lines presented in **Figures 36** and **37** are indicated in orange and yellow respectively.

Figure 36: Northwest segment of seismic line AGC 88-1 across the LaHave Platform, western Scotian Basin. The Sambro I-29 well (Union Oil, 1974) was drilled to test an interpreted highly-rotated fault block. Subsequent seismic data revealed that the feature was a faulted and eroded half graben. The ~1580 metres of presumed Late Triassic strata encountered below the Breakup Unconformity is composed of fluvial sandstones with increasing amounts of siltstones and shales with depth. These sediments have been designated as part of the mudstone-dominated Eurydice Formation, however, they are too coarse grained and are interpreted to be equivalent to the TS II Wolfville Formation of the Fundy Basin. The nearby Naskapi N-30 well (Shell, 1970) was drilled to test drape over a basement feature and ended in Middle Devonian granites. The higher amplitude events correlate with individual coarsening-upward sandstone intervals, and it remains unknown how much of the prerift Triassic-Jurassic strata was removed by erosion. There were no hydrocarbon shows, evaporites and basalts present in either of the wells. Interpretation modified after Keen *et al.* (1991).

Figure 37: Seismic profile across the Slope Diapiric Province, southwest Scotian Slope. The faulted succession beneath the Early Jurassic Breakup Unconformity (BU) is interpreted to be Late Triassic synrift strata. The high amplitude reflections show significant lateral continuity and their deeper position within this section suggests they may be lacustrine in origin, though may also be fluvial successions as shown in the previous figure. However, their association with overlying and conformable evaporites infers that this region was a depositional low and thus more prone to the formation of lakes. Though the possibility exists of these reflections being tholeiitic basalt flows, they do not display the same reflection character as shown by the basalts of the North Mountain Formation (Fundy Basin, **Figure 26**) nor correspond to any positive magnetic anomalies. Slightly modified after Deptuck (2011).

Figure 38: Paleogeographic map of the future Central Atlantic region at Early Carnian time (237-232 Mya). The Fundy basin extends from ~3-6°N in the northern part of the humid tropics. In the Newark Basin, the equivalent

Stockton Formation was being deposited at an equatorial position (~0-1°S). From its latitudinal position and seismic reflections, in the Fundy Basin the lower part of the Wolfville Formation (**Figures 28 & 29**) is interpreted to represent Richmond-type lacustrine complex deposited in an overfilled basin depositional setting. It is interpreted that the same should exist in the equivalent Stockton Formation. The green oval of potential pre-salt basins in the deep water offshore Nova Scotia shows that they are entirely within the humid tropics (1-3°N) where source rock intervals could potentially develop. Modified after Olsen (1997).

Figure 39: Paleogeographic map of the future Central Atlantic region at Late Carnian time (232-227 Mya). The Fundy Basin has drifted north and now extends from ~7-9°N and is within the subtropical climate belt. The Newark Basin has moved north but remains at a near equatorial position (~2-3°N). Seismic reflections in the upper part of the Wolfville Formation (**Figures 28 & 29**) are interpreted to represent Newark type lacustrine deposition (balanced filled basin type), with Richmond-type successions potentially being deposited in the Stockton Formation (overfilled basin type). The offshore pre-salt basin region has now transited into the transitional zone between the subtropical humid and arid belts and could have lacustrine successions similar to those in the Fundy Basin. Modified after Olsen (1997).

Figure 40: Paleogeographic map of the Central Atlantic region at Early Norian time (227-221 Mya). The Fundy Basin has drifted further north and now extends from ~9-11°N and is nearing the arid climate belt. The equivalent Lockatong Formation is in the northern part of the equatorial zone. Latitudinal position and seismic reflections in the Blomidon Formation (**Figures 28 & 29**) are interpreted to represent initial deposition under balanced filled lake basin setting (Newark type deposition) followed later by Fundy type deposition in underfilled basin conditions. It is possible that in the basin centre longer lived lakes with deeper-water lacustrine deposition may have existed throughout the entire Norian. Indeed, in the more southern Hartford basin, black lacustrine shales with organic material are present in its TS IV unit and at the same paleolatitude, though local geography, drainage and climate undoubtedly had a significant influence on the basin's lacustrine system (Dickneider *et al.*, 2003). The green oval of potential pre-salt basins in the deep water offshore Nova Scotia shows that they are entirely within the semi-arid zone (6-9°N) though could potentially develop source rock intervals at this time. Modified after Olsen (1997).

Figure 41: Well-known seismic depth profile of the Tupi-Iracema complex in the Santos Basin (Formigli, 2007). Post-breakup salt overlies the half grabens with possibly four tectonostratigraphic units separated by unconformities (two in each "Syn-rifte" unit). The lower unit 1 – Aratu / Buracica Sequence - is composed of fluvial sandstones, conglomerates, playa mudstones and volcanics, and represents the initial synrift succession. The upper unit 2 – Jiquia / Alagoas Sequence – is composed of interbedded lacustrine siliciclastic and limestone reservoirs (microbialites and coquinas) and organic-rich source rock shales. The Iracema and Tupi discoveries are believed to be a single accumulation containing 12-30+ billion Boe initial hydrocarbons in place (IHIP). The pre-salt section shares geometric and stratigraphic similarities with those of the Fundy-Chignecto and Newark basins (**Figure 33**); however, these basins are inboard of the main rift axis and salt basin. Similar half grabens likely exist under the thick salts of the Early Jurassic (Hettangian-age) Argo Formation in the offshore Scotian Basin, though here these evaporites are part of the pre-breakup sag phase. Modified after Formigli (2007).

Figure 42: Conclusions and Insights

- **TS II / III: interpreted lacustrine facies deposited in overfilled to balanced filled lake basins.**

Seismic profiles in the Newark and Fundy-Chignecto basins reveal near-identical structural geometries and tectonostratigraphic architectures reflecting the balancing influences of tectonism and climate. The seismic reflections in the lower Wolfville Formation (Early Carnian) are interpreted as representing deposition in an overfilled lake basin with a fluvial-lacustrine facies association / Richmond-type lake succession deposited at low paleolatitudes. The upper Wolfville (Late Carnian) was deposited in a balanced filled lake basin with resultant fluctuating profundal facies association / Newark type lake basin at a higher paleolatitude in a drier subtropical climate. Deposition of the younger Blomidon Formation (Early Norian) occurred under more arid conditions transitioning from a fluctuating profundal facies association / Newark type lake basin to evaporative lacustrine-playa / Fundy type association. Deep water lacustrine strata could exist in the basin centre throughout the period of Blomidon deposition.

- **Lake basin type, facies and proximity to equator considered to favour organic productivity.**

Middle to Late Triassic (Anisian-Carnian) TS II fluvial successions reveal high amplitude reflections in the basin centres that are interpreted as lacustrine sequences. This infers that the basins had significant tectonic extension from their inception. The paleolatitude for the depositional period of TS II Newark and Fundy basin fluvial-lacustrine successions places them into the tropic to subtropic climate zones. Together with the interpreted lake basin types (Overfilled to balanced filled), these climate conditions would be conducive to the creation of lakes and organic matter (coals and organic-rich black shales) in the Fundy basins as demonstrated in the southern Newark Supergroup basins. Late Triassic (Norian) TS III lacustrine / playa successions were deposited when the Newark Basin was in the northern part of the humid tropics (Lockatong Formation). The Fundy-Chignecto basin was in the northern part of the subtropical transition zone with its lacustrine facies reflecting increasing aridity as the basin drifted northwards into the arid belt Blomidon Formation). As noted previously, Blomidon successions could contain deep water lacustrine strata in the basin centre with creation and preservation of organic matter.

- **Key Chignecto Subbasin play elements identified with tectonic-induced fracturing within Carnian-Norian prospective interval.**

The interpreted Wolfville (TS II) and Blomidon (TS III) formation lacustrine successions are highly faulted, thus introducing fracturing and creation of reservoir characteristics (porosity and permeability). Conventional reservoirs of deep-water lacustrine sandstone turbidites may also be present in the Wolfville. Highly-rotated fault blocks incorporate the TS III lacustrine successions in a conventional structural trap configuration. Seals for all traps would be provided by overlying TS IV tholeiitic basalts and playa-lacustrine mudstones and shales. Hydrocarbon migration is internal into fractures and possible sandstones within the source rock successions.

- **Potential exists for Late Triassic source rocks for offshore Nova Scotia pre-salt plays**

Pre-salt plays sourced from Late Triassic to Early Jurassic rift systems offshore Nova Scotia may provide an intriguing play with similarities to the multi-billion barrel pre-salt plays of Brazil and West Africa. Offshore Brazil, supergiant oil fields have been discovered in continental pre-salt basins. There is a compelling similarity between the structural and stratigraphic architectures of the Newark and Fundy-Chignecto basins and the Brazilian basins based on their seismic expressions (albeit from limited available datasets). Nevertheless, should the expected continental basins beneath the prerift salts of the Hettangian Argo Formation offshore Nova Scotia be confirmed through modern 3D seismic programs (e.g. Shell: 2013-14, and BP: 2014-15), their paleolatitudinal position in the Late Triassic suggests the potential for overfilled and balanced filled lake basin types and related source rock development. Similar pre-salt, synrift half-grabens present offshore Eastern North America, Northwest Africa and Iberia may also contain source rock successions that could be significant contributors to their petroleum systems.

Figure 43: END Slide.

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