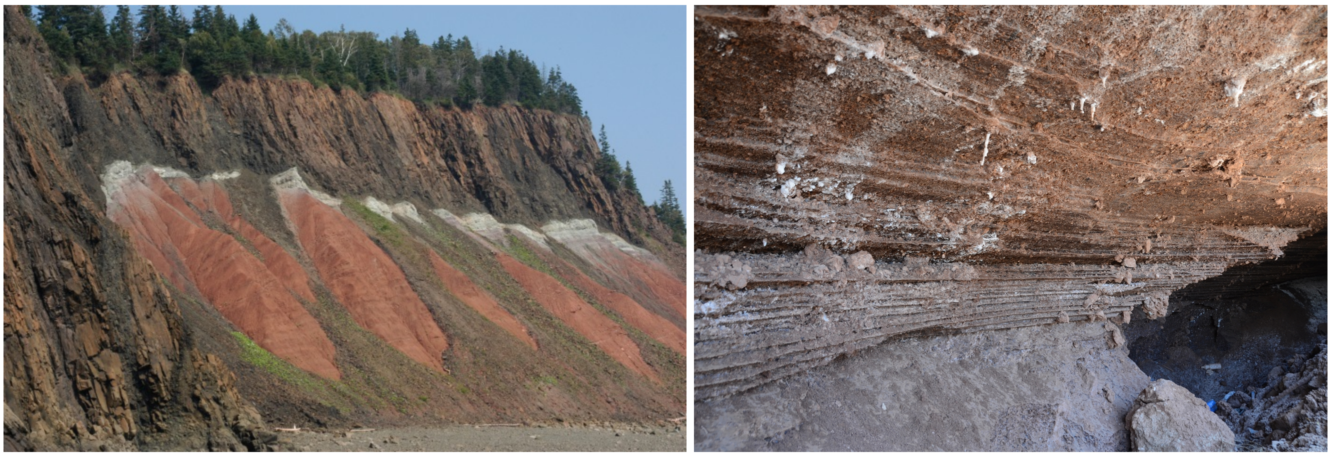
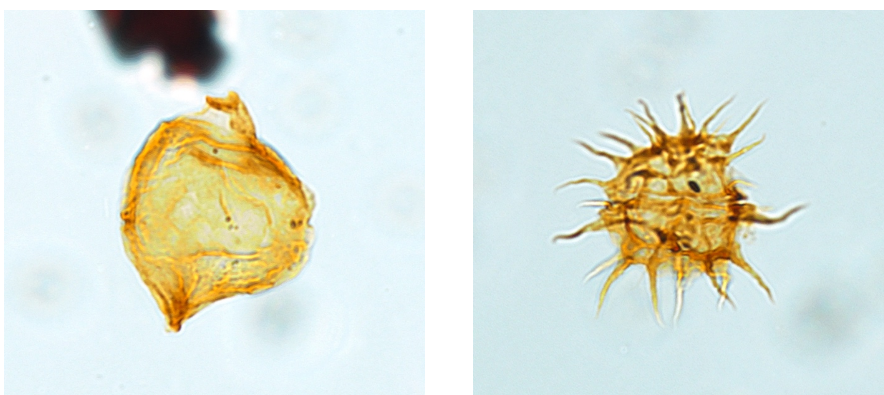
Upper Triassic-Lower Jurassic Central Atlantic Correlation



(Left) Uppermost Triassic Central Atlantic Magmatic Province basalts of the North Mountain Formation overlying Upper Triassic lacustrine redbeds of the Blomidon Formation, Five Islands, NS. **(Right)** Layered salt exposed in the Jebel Amsitten anticline at Ida-Ou-Azza salt pan in the Essaouira Basin, Morocco. Layers are ~10cm thick.



Example Early Jurassic dinoflagellates from the Cormorant N-83 well, Grand Banks of Newfoundland. *Nannoceratopsis* sp. (Left) and *Luehndea spinosa* (Right)

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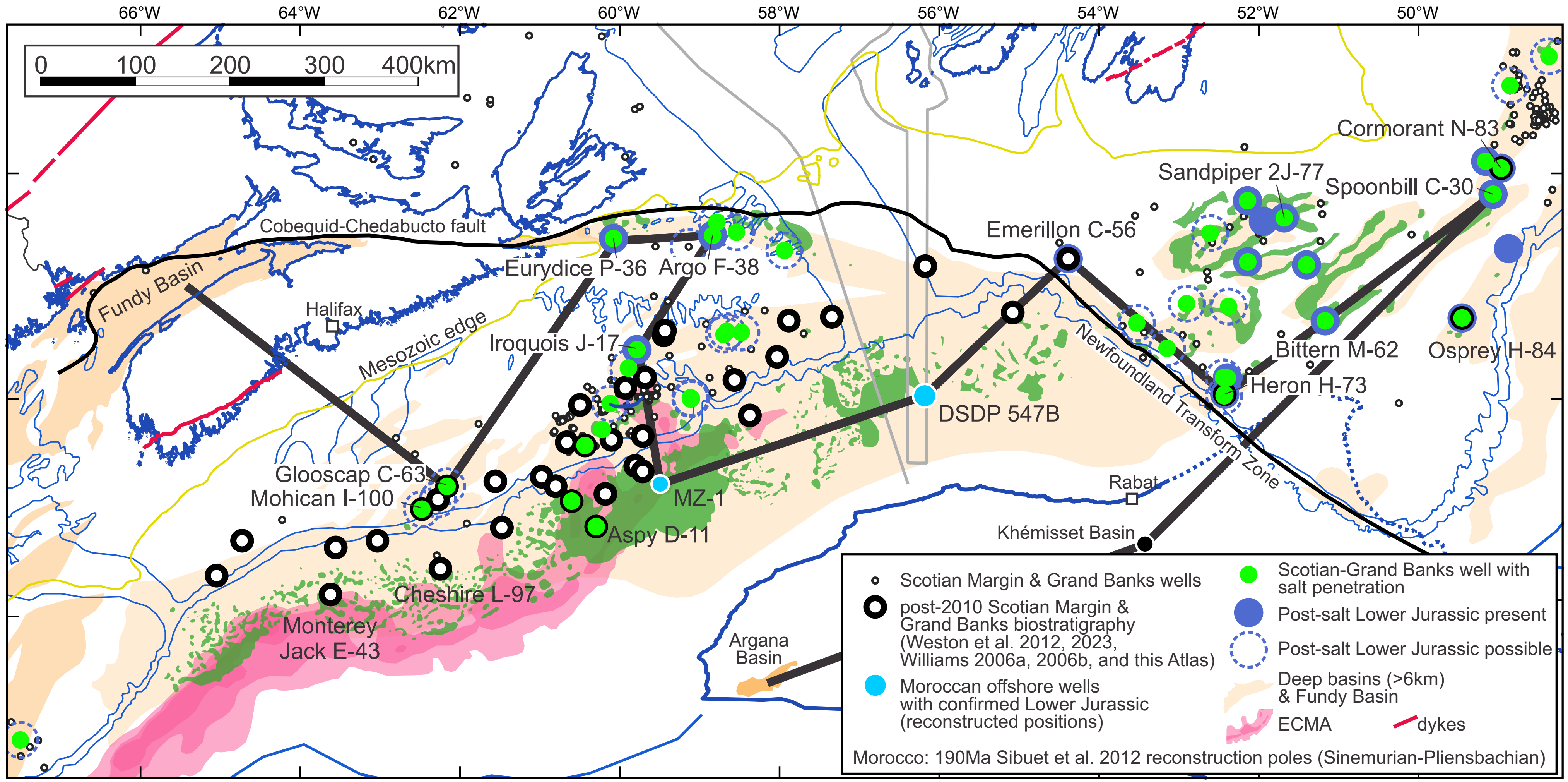
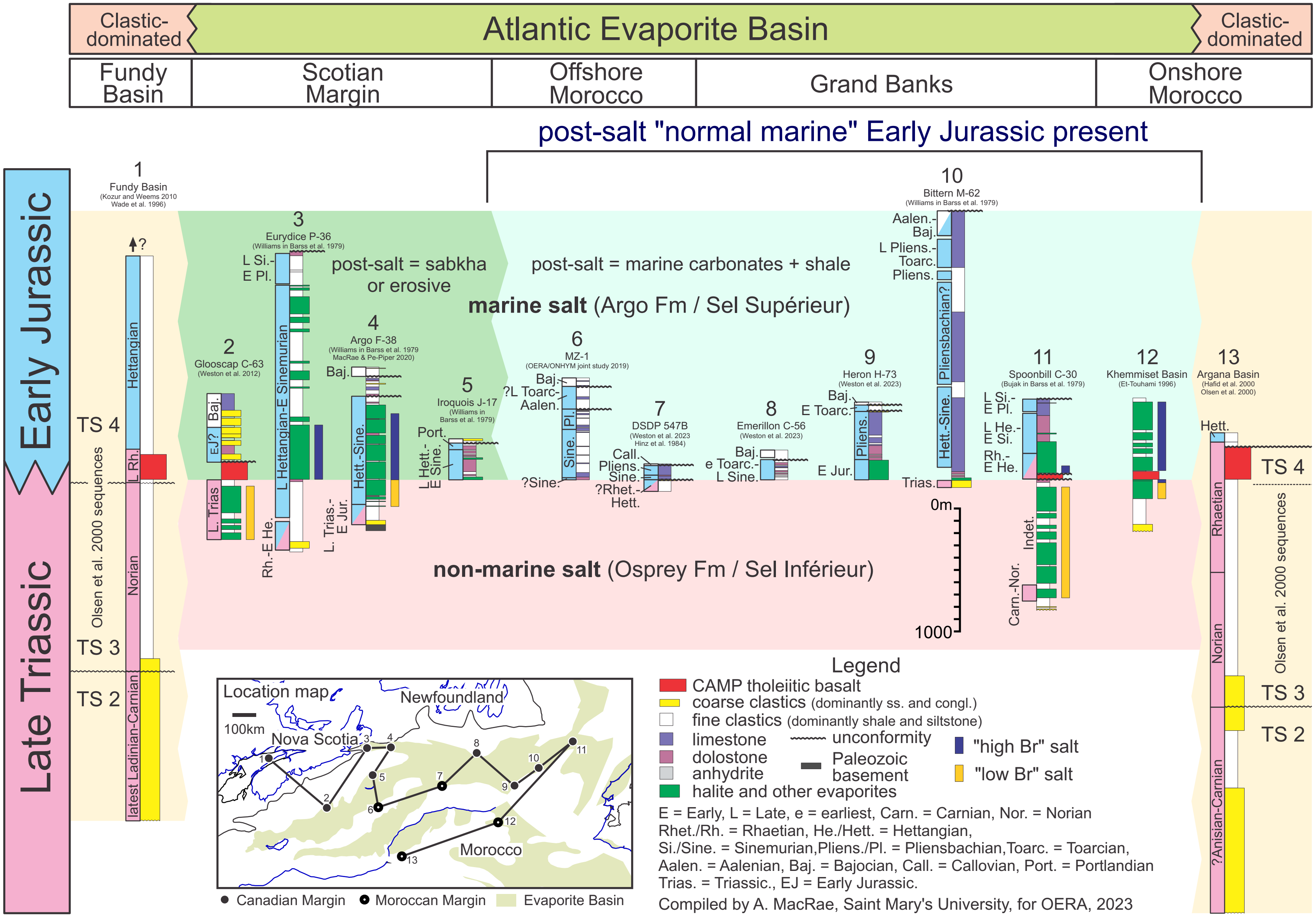
Location Map



Stratigraphic Correlation Chart



Introduction

This stratigraphic correlation chart depicts the correlation of Upper Triassic-Lower Jurassic salt- and clastic-dominated formations, and the post-salt Lower Jurassic formations, on the Nova Scotia, Grand Banks, and Moroccan margins. Well and outcrop sections are depicted at the same scale and greatly simplified from the available lithostratigraphic and biostratigraphic data to give an overview of the relationships. In general, lithostratigraphic data is obtained from cuttings descriptions in the original industry well history reports with some modifications, and outcrop sections from the cited literature. Several wells have been the subject of recent biostratigraphic study (Weston et al. 2023 and OERA/ONHYM 2019), while others rely on vintage data as far back as the 1970s (Barss et al. 1979).

This written report is organized in time from oldest to youngest and geographically from the Scotian Margin to Grand Banks and then the conjugate margins in each time interval. The stratigraphic chart is the main figure, but a map with key wells and Lower Jurassic strata penetrations is also supplied.

Biostratigraphic Limitations

The Late Triassic-Early Jurassic is a challenging time to study biostratigraphically because many of the sedimentary facies are either redbed fluvial/lacustrine clastics or evaporites, where normal marine floras and faunas are excluded. In these conditions, the only biostratigraphic tools available from wells are pollen and spores from palynology. Coupled with intermittent barren zones and the usual limitations of industry cuttings sample contamination (only stratigraphic tops of species are reliable), less-certain age calls are common (generalized "Early Jurassic" or lengthy stage-level age calls). This issue is discussed more extensively in Weston et al. (2012) on the Scotian Margin, but it applies throughout the local region and the conjugate margins over much of this interval. The problem also highlights the potential value of future palynology studies from outcrop in Nova Scotia and/or Morocco to better refine the local terrestrial palynology events in comparison to better-studied European and western USA locations.

Once normal marine salinity conditions spread into the area (generally in Sinemurian times -- see below), a more complete biostratigraphic suite is present (dinoflagellates, nannofossils, foraminifera and other microfossils), and age calls become more reliable at stage level or better precision, but preservation and penetration of these sediments by offshore wells is uncommon and geographically restricted (mainly the Grand Banks and Morocco). Outside these areas, coeval Lower Jurassic strata likely exists, but represents less biostratigraphically productive facies (e.g., marine-marginal sabkha coastlines or continental) and will have more uncertain ages as a result. These caveats should be kept in mind when assessing all the correlations and timings hypothesized here.

Salt and Syn-Salt Stratigraphic Relationships (Late Triassic-earliest Jurassic times)

In general, inboard locations (Fundy Basin, Nova Scotia and Argana Basin, Morocco) are clastic-dominated and multiple kilometres thick within fault-bounded, syn-rift fluvial and lacustrine basins (Wade et al. 1996, Olsen et al. 2000, Hafid 2000, Leleu et al. 2016). These units have been subdivided into a succession of four unconformity-bounded tectono-stratigraphic sequences (TS1 to TS4) by Olsen et al. (2000) that are thought to be tectonically-controlled and synchronous on the conjugate margins.

The more central locations, closer to the nascent Central Atlantic, are characterized by thick (sometimes kilometres), halite-dominated evaporites of two main types within the "Atlantic Evaporite

Basin", an area of salt deposition that extends along the entire conjugate eastern North American and western African margins (Central Atlantic) and north onto the Grand Banks and Iberia conjugate margins. Salt tectonics is extensively developed and documented in these areas (Deptuck and Kendell 2017, 2022, Tari et al. 2017, Balkwill and Legall 1989, Alves et al. 2003, Decalf and Heyn 2023, Cawood et al. 2022), affecting almost all the later basin history, but the initial salt stratigraphy has received relatively little attention by comparison. The salt-dominated units are interbedded with redbed clastic units (Eurydice Formation) that are similar to the onshore clastic-dominated basins, as well as minor amounts of carbonates (limestone and dolostone), gypsum, anhydrite, grey shales, and rare carnalite (Wade and MacLean 1990, McAlpine 1990, Decalf and Heyn 2023).

Holser et al. (1988) and Jansa et al. (1980) recognized that salt on the Grand Banks consists of a lower, low-bromine-concentration (<60ppm) salt unit that is likely of continental origin (i.e. saline rift lakes), succeeded by a high-bromine salt unit (>60ppm) likely of marine origin. The lower formation is typically Upper Triassic in age (Carnian-Norian-Rhaetian) and is known as the Osprey Formation (Jansa et al. 1980, McAlpine 1990), whereas the upper formation is typically Lower Jurassic in age (Hettangian-?early Sinemurian) and assigned to the Argo Formation (McIver 1972, McAlpine 1990, Wade and MacLean 1990). The Osprey Formation type section is in the Osprey H-84 well on the Grand Banks, whereas the Argo Formation type section is in the Argo F-38 well in the Orpheus Graben on the Scotian Margin. Traditionally (Wade and MacLean 1990), all of the salt on the Scotian Margin is assigned to the Argo Formation, however, recent work has indicated that the same "two salt" stratigraphy occurs on the Scotian Margin as on the Grand Banks, though both salts are not always present in any given section. Much of the detail of this interpretation for the Scotian Margin is only published in abstracts (MacRae et al. 2013, MacRae and Pe-Piper 2020 and 2022), but some recent publications dealing with the broader stratigraphy of the region have also recognized the transition from "continental salt" to "marine salt" is more widespread than the Grand Banks alone (e.g., Leleu et al. 2016).

Between the two salt formations in multiple wells on the Grand Banks (e.g., Spoonbill C-30 and Cormorant N-83) are tholeiitic basalts of the Central Atlantic Magmatic Province (CAMP; Pe-Piper and Jansa 1987, Pe-Piper et al. 1992). A similar pattern occurs at the Glooscap C-63 well on the Scotian Margin, where the tholeiitic Glooscap Volcanics occur, but without an overlying marine salt unit present (Pe-Piper and Jansa 1987, Pe-Piper et al. 1992, Deptuck and Altheim 2018). Only the low-bromine, continental Upper Triassic salt is present beneath the CAMP basalt at this well (likely assignable to Osprey Formation, MacRae and Pe-Piper 2020), and it also occurs extensively within basins of the LaHave Platform area according to seismic interpretation (Deptuck and Altheim 2018). Away from this area, the younger salt (Argo Formation) is the main unit penetrated by wells (see figure) and is likely the thicker of the units on the Scotian Margin based on seismic (Deptuck and Altheim 2018, Deptuck and Kendell 2017, 2022). One other well (Aspy D-11, Decalf and Heyn 2023) also penetrates basalt within the salt, though it is in a highly deformed allochthonous canopy, so its stratigraphic position is unclear.

On the Moroccan Margin, CAMP basalts are extensively present within the salt of the onshore Essaouira (Hafid 2000), Berrechid (Afenzar and Rachid 2017, Lyazidi et al. 2003), and Khémisset basins (Et-Touhami et al. 1996), with the salt below referred to as the "Sel Inférieur" and the overlying salt the "Sel Supérieur". Within the Khémisset Basin, the Sel Inférieur is characterized by low bromine concentrations over most of its thickness, rising to higher (>60ppm) values only near its top, whereas the Sel Supérieur has higher bromine concentrations (Et-Touhami 1996), broadly consistent with the pattern seen on the conjugate Canadian margins. On both the Canadian and Moroccan margins, the main CAMP eruption is assessed to commence close to the Triassic-Jurassic boundary, at the beginning of the end-Triassic mass extinction, the boundary itself marking the extinction recovery (Blackburn et al. 2013).

Taken together, the geochemical, biostratigraphic, and stratigraphic relationships with the CAMP suggest that the transition from continental salt (Osprey Fm/Sel Inférieur) to marine salt (Argo Fm/Sel Supérieur) occurs close to the Triassic-Jurassic boundary, approximately coeval with the peak of CAMP eruption. On the Moroccan margin, multiple CAMP units occur in some areas (e.g., the Essaouira Basin -- see Hafid 2000), suggesting some caution is needed when using this generalization, and additional biostratigraphic and geochemical work is needed to thoroughly test the hypothesis.

The correlation chart depicted here uses the boundary between the two geochemically distinct salt units and the CAMP as a datum, hypothetically corresponding to the Triassic-Jurassic boundary, but as can be seen from the available biostratigraphic data and its uncertainties, it can only be considered an approximate one.

A coincidence between the timing of CAMP and the transition between continental and marine salt basin makes sense with the expected beginning of ocean spreading and the increasingly likely invasion of the global ocean into the Central Atlantic as the basin continued to widen, however, whether the marine salt invasion was truly synchronous or a progressive/diachronous invasion into individual basins of the region is not resolvable with current data. Both scenarios are known for other salt basins, such as the Gulf of California (Umhoefer et al. 2018, progressive invasion) or the Red Sea (Almalki et al. 2015, nearly synchronous and eustatically-controlled for the main salt), but these relationships were resolvable only thanks to the availability of high-resolution biostratigraphic data in the Neogene.

Post-Salt Lower Jurassic

The timing of first normal marine invasion in the Central Atlantic (i.e. post-evaporite) is difficult to constrain from Scotian Margin data due to the previously-mentioned dominance of facies with poor biostratigraphic recovery. Although post-salt Lower Jurassic is identified (Weston et al. 2012), it largely consists of dolostone, anhydrite, and clastics of the Iroquois and Mohican formations, interpreted as sabkha to fluvial and coastal or deltaic facies (Jansa and Wade 1975, Wade and MacLean 1990, OERA 2011), that yield only non-marine palynomorphs, and therefore low-resolution age information. Examples of these post-salt Lower Jurassic facies and biostratigraphic control are present at the Glooscap C-63, Mohican I-100 (stratigraphy not shown), Iroquois J-17, Eurydice P-36, and Argo F-38 wells (Barss et al. 1979, Weston et al. 2012, MacRae et al. 2013). In Barss et al. (1979) and Bujak and Williams (1977), this post-salt interval was mainly assigned to their *Echinitosporites* cf. *iliacoides* Zone and tentatively given a late Sinemurian-early Pliensbachian age based on limited non-marine palynomorph markers. The only known biostratigraphic evidence for "normal marine" Lower Jurassic on the Scotian Margin is in the form of reworked Early Jurassic nannofossils in the South Griffin J-13 well (Weston et al. 2012), implying that such rocks were deposited in the area, but may have been subsequently removed by erosion (area labelled "post-salt = sabkha or erosive" on the chart).

By contrast, unambiguous normal marine Lower Jurassic strata is known from multiple wells on the southern Grand Banks of Newfoundland within limestone and shales assigned to either the Iroquois or Downing formations (labelled “post-salt marine carbonates + shale”, McAlpine 1990). Example wells include Emerillon C-56 and Heron H-73 (Weston et al. 2023), Bittern M-62 and Spoonbill C-30 (Barss et al. 1979), and Cormorant N-83 and Osprey H-84 (Williams 2006a, 2006b). Dinoflagellates from palynology and some nannofossil results demonstrate Sinemurian, Pliensbachian, and Toarcian ages in normal marine salinity conditions at these wells. The Bittern M-62 well is particularly notable for its thick (>1km) post-salt Lower Jurassic that was also the subject of a recent carbon-isotope study (see this Atlas). The oldest post-salt, normal marine evidence in the Grand Banks area therefore appears to be Sinemurian.

Normal marine Lower Jurassic is also known from the conjugate Moroccan margin at the DSDP Leg 547B borehole (Hinz et al. 1984, Robinson et al. 2017, Weston et al. 2023), and from offshore industry wells (e.g., MZ-1, OERA/ONHYM 2019), where clear Sinemurian, Pliensbachian, and Toarcian normal marine strata are penetrated with good biostratigraphic control from palynology, nannofossils, and foraminifera, though not usually the entirety of each stage is represented due to unconformities. The oldest and clearest example of these ages is within the DSDP Leg 547B borehole because of the conventionally-cored samples, where the oldest age for normal marine strata is within the late Sinemurian and continues into the Pliensbachian, based on nannofossils and palynology (Weston et al. 2023, Robinson et al. 2017, Hinz et al. 1984). The final end of the Atlantic Evaporite Basin and beginning of normal ocean salinities therefore appears to be an intra-Sinemurian event.

This interpretation is broadly consistent with evidence for the establishment of the so-called "Hispanic Corridor", linking Early Jurassic European marine faunas to the Caribbean through the Central Atlantic, which had definitely occurred by Pliensbachian times (Smith 1983), but where there is some debate over whether it could have been as early as Sinemurian or even Hettangian. Most authors favor the Central Atlantic remaining a significant barrier to ocean migration due to physical barrier or still-ongoing hypersaline conditions until sometime in the late Sinemurian (Porter et al. 2013), although intermittent connectivity through earlier intervals remains a possibility even within older, otherwise evaporite-dominated intervals (MacRae and Pe-Piper 2020, 2022).

Summary and Implications for Early Atlantic History

In summary, the early Atlantic Basin was initially a continental rift basin with its central portions occupied by saline lakes that deposited significant evaporites in the form of salt on the Scotian, Grand Banks, and Moroccan margins. This evaporite system evolved into a marine evaporite basin roughly coincident with the Triassic-Jurassic boundary, the peak of CAMP eruption, and probably near the time of transition to ocean spreading. As the Atlantic Ocean continued to open, marine evaporite deposition ceased as normal marine circulation began, probably within the Sinemurian. This set the conditions for potential marine source rock production within the narrow, early, post-salt Atlantic marine basin, including possibly within the well-known Toarcian ocean anoxic event, but the exact details depend on basin oceanography, tectonic subsidence, and preservation, including the possible effect of subsequent erosion. Though the Lower Jurassic of these regions is cryptic because of the limited number of well penetrations, improved study is beginning to develop a clearer picture of the earliest history of this part of the Atlantic.

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