Earliest sedimentological evidence for marine ingression in the eastern North American rift system, Central Atlantic Margin

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ABSTRACT

A current debate concerns the timing and dynamics of marine ingression into the rift basins of the Central Atlantic Margin. Two scenarios of evolution are hypothesized for Late Norian to Rhaetian paleogeographic reconstructions: (i) marine ingression leading to salt generation through evaporation of seawater, or (ii) salt generation through groundwater evaporation within basins located far from marine influence. These hypotheses remain unproven.

Along the northern margin of the Central Atlantic Margin, the so-called eastern North American rift system, the dolostone-dominated Iroquois Formation is the first unequivocal evidence of marine-influenced sedimentation. Age of this unit is not consensual, but it is dated as Early to Middle Jurassic. Our investigation of two cores (assumed here to be of Rhaetian age) from the Eurydice Formation in the Scotian and Orpheus basins provides the first convincing sedimentological evidence of Late Triassic marine ingression into the eastern North American rift system. This was likely contemporaneous with the main transgressive events recorded in Western Europe. Evidence suggests the studied interval of Eurydice Formation was deposited by tide-dominated processes, possibly in an estuarine or deltaic environment.

This work challenges the vision of a linear evolution of Central Atlantic Margin basins during the early stages of continental break-up and rifting; instead this story seems to be punctuated by marked and recurring changes in the depositional environments. Our findings have far reaching implications for the understanding of Triassic–Jurassic paleogeography and paleoclimates, biological evolution, and resources exploration. Additionally, these findings may have regional consideration for the development of major marine evaporite build-ups and the timing of initial marine ingression during rift basin development.

INTRODUCTION

Regional extension during the early Mesozoic initiated fragmentation of Pangaea and created a series of rift basins extending from southern North America and central Africa to Greenland and Spitzbergen (Jansa and Wade, 1975; Olsen, 1997). Typically, the Triassic record of these basins is buried under kilometers of sediments (e.g., Jansa et al., 1980; McAlpine, 1990; Olsen, 1997; Leleu et al., 2016), making the investigation of the early evolution of the Central Atlantic Margins (CAM, as defined by Olsen, 1997) problematic.

There is debate concerning the timing of first marine ingression into the CAM. The most recent review regarding Triassic evolution of these margins demonstrated the ambiguity of depositional environments and timing of marine flooding.

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Leleu et al. (2016) hypothesized two scenarios for Late Norian to Rhaetian paleogeographic reconstruction: (i) marine ingression leading to salt generation through evaporation of seawater, or (ii) salt generation through groundwater evaporation within basins far from marine influence. These hypotheses remain unproven to date.

The Scotian and Orpheus basins (offshore Nova Scotia, Canada) are the two northernmost basins of the central segment of the Eastern North American Rift System (ENARS, as defined by Withjack et al., 2012) (Olsen, 1997) (Fig. 1A). Given the proximity to the Tethys Ocean, the two basins (Fig. 1B) may record Triassic flooding events observed in several European sections (e.g., Gianolla and Jacquin, 1998; Orti et al., 2017).

In this paper, we present detailed sedimentological evidence from the only two cores recovered from the Upper Triassic–lowermost Jurassic Eurydice Formation. Each core comprises ~9 m of siliciclastic deposits from the Eurydice Formation. In the Orpheus Basin, a core from the Eurydice P-36 well (Figs. 1 and 2) was recovered ~600 m below the base of the Argo Formation dated from the Early Jurassic (Shell Canada Limited, 1971; Barss et al., 1979). In the Scotian Basin, a core from the Mohican I-100 well (Figs. 1 and 3) was recovered ~5 m above a salt interval of interpreted Late Triassic age (Shell Canada Limited, 1972; Weston et al., 2012). The Eurydice and Argo formations are capped by the dolostone-dominated Iroquois Formation (Fig. 1C), which is the first unequivocal evidence of marine-influenced sedimentation in the Scotian and Orpheus basins (Weston et al., 2012). However, on the basis of geochemical evidence (high Br content indicating crystallization from sea water), salts dated from the Early Jurassic are interpreted as marine in origin and could therefore be recognized as the first indication of marine incursion in the central segment.
The Scotian Basin is a submarine rift to passive margin basin that extends northeast from the eastern flanks of Georges Bank to the central Grand Banks, covering a distance of 1200 km and an area of nearly 300,000 km² (Wade and MacLean, 1990). The basin is an accreted wedge of Mesozoic marine incursion into the ENARS and CAM.

**GEOLICAL BACKGROUND**

The Scotian Basin is a submarine rift to passive margin basin that extends northeast from the eastern flanks of Georges Bank to the central Grand Banks, covering a distance of 1200 km and an area of nearly 300,000 km² (Wade and MacLean, 1990). The basin is an accreted wedge of Mesozoic–Cenozoic sediment collected in a series of interconnected subbasin depocenters structurally bordered to the northeast, northwest, and southwest (Jansa and Wade, 1975; Wade and MacLean, 1990). The basin contains 12–18 km of Triassic to Quaternary sediments above metasedimentary and igneous basement (Jansa and Wade, 1975; Wade and MacLean, 1990).

The Orpheus Basin is a submarine, eastward-plunging and widening, rift to passive margin basin (Wade and MacLean, 1990; Tanner and Brown, 2003) (Fig. 1B). It is ~300 km in length and widens from its onshore western apex of several hundred meters to 60 km in the east (Tanner and Brown, 2003; Withjack et al., 2012). It is bounded to the north and south by a series of discontinuous, subparallel faults (Tanner and Brown, 2003; Jansa and Wade, 1975). The Orpheus Basin contains ~10 km of Triassic to Quaternary sediments above metasedimentary and igneous basement (Jansa and Wade, 1975; Lyngberg, 1984; Wade and MacLean, 1990; Tanner and Brown, 2003).

The oldest sediments in the Scotian and Orpheus basins are the synrift continental siliciclastics of the Eurydice Formation (Jansa and Wade, 1975; Wade and MacLean, 1990). In the Scotian Basin, seismic and well data indicate that the Eurydice Formation is widespread along the margin, and although variable, can be in excess of 1500 m thick (Union Oil Company of Canada Limited, 1975; Williams et al., 1985). In the Orpheus Basin, seismic data indicate that this unit is up to ~3 km thick (Jansa and Wade, 1975; Wade and MacLean, 1990). Tanner and Brown (1993, 2003) divided the formation into two informal tectonostratigraphic intervals: (i) an Anisian (possibly Permian)–Norian lower interval (sequence A1) (undrilled and assumed as coarse-grained fluvial and alluvial siliciclastics), and (ii) an upper Rhaetian–lowermost Hettangian upper interval (sequence A2), dated by palynological analysis (Bujak and Williams, 1977; Barss et al., 1979). This formation is conformably overlain and locally interfingers with Hettangian–lower Sinemurian evaporites of the Argo Formation (sequence B1), which are, in turn, overlain by post-rift marginal marine, passive-margin shelf sediments (sequence B2) (Jansa and Wade, 1975; Tanner and Brown, 2003) (Fig. 1C).

The type section for the Eurydice Formation was defined in the Eurydice P-36 well of the Orpheus Graben (Figs. 1 and 2). This well penetrated ~600 m of red sandstone, siltstone, and shale (Shell Canada Limited, 1971; Jansa and Wade, 1975; Williams et al., 1985). A single core (~8.75 m) was recovered at the base of the type section, consisting of anhydrite nodules-rich sandstones, muddy sandstones, and mudstones, interpreted in the literature to represent a terrestrial saline (playa) mudflat (Shell Canada Limited, 1971; Wade and MacLean, 1990; MacLean and Wade, 1993; Tanner and Brown, 2003).

**MATERIALS AND METHODS**

The cores from wells Eurydice P-36 and Mohican I-100 (core #9) were logged in detail.
Figure 2. Schematic and photographic representation of the Eurydice Formation type section from the core of the Eurydice P-36 well. (A) Eurydice P-36 core log, sedimentary features, location of associated photos, and interpreted facies. (B) Heterolithic bedding perturbed at the base and undisturbed at the top. The top of the image shows tidal bundles, with thin sand and mud couplets at the base moving upwards into thicker sand and thin mud couplets. (C) Representative heterolithic bedding found in the core. Perturbed at the base (bioturbated?), lenticular/wavy bedding in the middle, and flaser bedding at the top. (D) Cross-laminated sandstone with bipolar- or obliquely oriented (apparent herringbone) cross-lamination with reactivation surfaces and thin mud drapes along cross-bed foresets. (E) Featureless mudstone/siltstone with the occurrence of mm-sized evaporitic nodules and some thin laminated sands. S—silt; F—fine-grained sand; M—medium-grained sand; C—coarse-grained sand.
for lithology (color, grain size, and mineral composition), physical and biogenic sedimentary structures, and all surfaces or boundaries (Figs. 2 and 3). Sediments of similar lithology were grouped into descriptive facies and each facies association was interpreted in terms of its process and depositional environment.

RESULTS AND DISCUSSION

Summary of Facies and Facies Associations

Three representative facies forming a single facies association are recognized in the core.

**Facies 1: Heterolithic Sandstone and Siltstone**

**Description.** Facies 1 (F1) comprises alternate layers of reddish-brown, featureless siltstone/mudstone and yellowish-brown, very fine-to fine-grained, cross-bedded sandstone (Figs. 2B, 2C, 3B, and 3D). The beds are 5–50 cm thick, show mild bioturbation, and form lenticular, wavy, and flaser heterolithic bedding. The siltstone layers contain small (<1 mm) anhydrite nodules. Cross-strata have sharp basal and wavy upper contacts. A single shell fragment (3 cm in length) and perturbated beds are evident in the Eurydice P-36 core (Fig. 4). Small (~1 mm) silt rip-up clasts are present along with sandstone cross-bed foresets. Perturbation is associated with moderate to intense bioturbation: Anconichnus, Diplocraterion, Skolithos, Palaeophycus, Teichichnus, and Planolites were identified (Fig. 4). This facies comprises ~35% of well Eurydice P-36 and 15% of core #9 of well Mohican I-100.

**Interpretation.** The alternate layers represent heterolithic bedding (flaser, wavy, and lenticular) formed during mixed energy deposition (Figs. 2B, 2C, and 3D). Based on the presence of alternate layers of sandstone and siltstone/mudstone, this facies is known to occur in either a tidal, fluvial, or mixed tidal-fluvial system (Visser, M.J., 1980; Nio and Yang, 1991; Fisher et al., 2008; Leleu and Hartley, 2010). If tidal in origin, these reflect the flood, slack, ebb, and slack conditions of stacked tidal cycles (Davis, 2012). During flood and ebb tides, strong currents moved and deposited coarse sediment, typically sand, and disturbed and eroded underlying silts and muds to incorporate them into the sandy bedforms as rip-up clasts. Between flood and ebb tides, standing (slack) water deposited fine grained silt and mud from suspension (Nio and Yang, 1991). The pattern of alternate layers of sand and mud produce tidal rhythmites, and together with the change from lenticular-wavy to flaser-wavy bedding (Figs. 2C and 3D), may
be an indication of systematic change in tidal strength over a short time interval (Longhitano et al. 2012). Additionally, the environmental significance of the trace fossils, although not definitive, suggest a marine signature (Gingras and MacEachern, 2012).

Contrary to this, these heterolithic beds may have formed during seasonally active rivers. Sands would have deposited during periods of high energy fluvial activity and muds during periods of waning fluvial strength (Thomas et al., 1987, and references within; Fisher et al., 2008; Leleu and Hartley, 2010). Anhydrite nodules indicate that the system was under evaporitic stress.

**Facies 2: Cross-Laminated Sandstone**

**Description.** Facies 2 (F2) comprises cross-laminated, 2–40 cm thick beds of very fine- to fine-grained, yellowish-brown silty-sandstone. Preserved physical sedimentary structures include trough and oblique-oriented (apparent herringbone) cross-lamination (height range of bedforms is between 7–15 mm), reactivation surfaces, and thin, sometimes coupled mud drapes along foresets (Figs. 2D and 3B). Siltstone laminae (<5 mm) are also present. The beds are occasionally perturbated, and cross-lamination can be vague in these intervals. This facies comprises ~15% of well Eurydice P-36 and 10% of core #9 of well Mohican I-100.

**Interpretation.** The preserved cross lamina-tions and presence of mud drapes and occasional mud rip-up clasts in this sandstone-dominated facies are known to occur in dominantly high energy fluvial, tidal, or mixed fluvial-tidal systems. During flood and ebb tides, coarse-grained sediment, mostly sand, was transported and deposited in migrating bedforms (Nio and Yang, 1991). During periods of slack water, between flood and ebb tides, mud settled from suspension as drapes between cross-bed foresets (Fig. 2D and 3B). Additionally, the pairing of muddy drapes (flood and ebb couplets) (Fig. 3B) indicates tidal affinity (Nio and Yang, 1991; Longhitano et al. 2012). Apparent herringbone cross-stratification (Fig. 2D) likely formed during opposing or obliquely oriented currents of flood and ebb tides. As the bedforms migrated with flood and ebb currents, the direction of the cross-strata changed to reflect these currents (Davis, 2012). The reactivation surfaces formed as a weaker ebb or flood tide was not strong enough to reverse the opposing bedforms but instead eroded and scoured their upper portion, leaving an erosional or undulating surface (Nio and Yang, 1991; Davis, 2012). The scale at which these preserved features are found (mm to a couple of cm’s) are documented in previous studies and suggest deposition under micro-tidal conditions (Brettle et al. 2002).

These preserved sedimentary features are also known to have been produced in unidirectional environments such as streams or rivers (Alam et al., 1985; Nio and Yang, 1991; Davis, 2012). As stated by Davis (2012), misinterpretation of...
bidirectional processes can occur when observing nested sets of trough cross-beds where apparent herringbone may be present. Additionally, Alam et al. (1985) have shown that in some dryland rivers, flow from a flooding mainstream may move up a tributary, depositing cross-beds in an apparently upflow direction. Nio and Yang (1991), Longhitano et al. (2012), and Davis (2012) all note that mud drapes and reactivation surfaces may also form in unidirectional streams and rivers.

**Facies 3: Poorly Stratified to Featureless Sandy Siltstone**

**Description.** Facies 3 (F3) comprises poorly stratified to featureless, up to 1 m thick beds of reddish-brown siltstone/mudstone, very fine-grained sandstone, and 1 mm to 5 cm sized anhydrite nodules (Fig. 2E). Paint stratification is marked by thin sandstone (Fig. 3C) and sub-parallel aligned, elongate anhydrite nodules. Occasional fine-grained sandstone and sporadic anhydrite nodules typically show no preferred orientation. Irregular wavy bedding (1–3 mm in thickness and gray in color) and perturbation of the unit are evident but rare. This facies comprises ~50% of well Eurydice P-36 and 75% of core #9 of well Mohican I-100.

**Interpretation.** The predominant occurrence of thick mudstone/siltstone typically represents suspended sediment settling in a low-energy environment (Nichols, 2009; Longhitano et al., 2012). The rare occurrence of fine-grained sand suggests deposition by sporadic higher energy mechanisms and may represent fluctuations of energy in the depositional environment (Longhitano et al., 2012). Anhydrite nodules indicate arid climatic conditions and the evaporation of seawater or highly saline groundwater (Nichols, 2009). Irregular bedding resembles possible deposition of microbial mats.

**Facies Association**

**Tidal facies association.** A review of diagnostic features of tidal deposits in subtidal environments by De Boer et al. (1989), Nio and Yang (1991), Nichols (2009), and Davis (2012) specify the following features as unique to tidal processes: mud couplets (occasionally paired) (Figs. 2D and 3B), rhythmic tidal-bundle successions with tidal signatures (Fig. 3B), and reactivation surfaces (Figs. 2D and 3B). Additional criteria include flaser, wavy, and lenticular bedding (Figs. 2C and 3D), herringbone cross-beding (possible interpretation Fig. 2D), and sigmoidal bedding (cryptic tidal signatures shown in Fig. 3D).

Based on diagnostic criteria from Nio and Yang (1991), Longhitano et al. (2012), and Davis (2012), the identified facies (Figs. 2 and 3) are interpreted to define a tidal facies association. Mud drapes and mud couplets of the heterolithic sandstone and siltstone (F1) and the cross-laminated sandstone (F2) facies indicate deposition under a mixed energy regime (i.e., between ebb and flood tidal currents). Cross-laminated bedforms in the sand rich successions were deposited in higher energy (i.e., during tidal currents) regimes, while the featureless mudstone and siltstone (F3) successions were deposited in lower energy slack water environments, likely along the landward margins of the system. These sedimentary features, along with the presence of interpreted trace fossils assemblages (Facies 1), suggest that the successions were deposited in a mixed energy tidal regime, most likely in a marine-influenced estuarine/deltaic environment (Nichols, 2009; Longhitano et al., 2012).

It is important to note the possibility of deposition of these successions in a continental fluvial setting. The presence of lenticular, wavy, and flaser bedding has been interpreted in fluvial depositional settings (Fisher et al. 2008; Leleu and Hartley 2010), while Davis (2012) emphasized that bidirectional features (i.e., herringbone cross stratification) can often be misidentified in a 2D core when observing nested sets of fluvial-derived trough cross-beds. Although, on an individual basis, these features are ambiguous when used to discern the environments during deposition, the interpretations made within the current study used the combined presence of features mentioned above in addition to features unique to tidal processes (see previous two paragraphs). Additionally, the presence of a possible specimen of dinocyst Rhaetogonyaulax cf. arctica in the core (Weston et al. 2012) adds to the strong likelihood that these successions are tidally derived.

**EARLIEST EVIDENCE OF MARINE FLOODING IN THE CENTRAL SEGMENT OF THE ENARS**

In the ENARS, namely in the offshore areas of the northeastern United States, Nova Scotia, and southern Newfoundland (Fig. 1B), some of the earliest sedimentary successions comprise thick evaporitic deposits of Triassic–Jurassic age (Jansa and Wade, 1975; Holser et al., 1988; McAlpine, 1990). Chemical analysis from the Grand Banks region (northern segment of the ENARS, Figs. 1B and 4) indicates that the Rhaetian–Lowermost Jurassic evaporites of the Argo Formation are of marine origin due to their high Br content. Stratigraphically below the Argo Formation, Upper Triassic evaporites of the Osprey Formation (Fig. 5) consistently show low Br contents. Given its low bromide and anhydrite contents, Holser et al. (1988) suggested that the Osprey Formation corresponds to second-cycle deposition (from the dissolution of the Carboniferous Windsor Group) in a non-marine basin. In a similar geochemical study performed in the Scotian Basin (central segment of the ENARS), MacRae et al. (2014) observed that Late Triassic salt at well Glooscap C-63 is probably equivalent to the Grand Banks Osprey Formation (low Br content) and that all other studied sites with Early Jurassic ages are consistent with their assignment to the marine-derived Argo Formation (Figs. 1B and 4). Further south, in the Georges Bank platform (Figs. 1B and 4) the Continental Offshore Stratigraphic Test (COST) No. 2-G well encountered salt of unknown origin at its base (Amato and Simonis, 1980). Recent studies suggest an Early Jurassic age for the carbonate unit overlaying the salt (OERA, 2015), but there is no definitive age assignment for the salt unit itself. Salt is found further south along CAM (Figs. 1A and 1B), but is either interpreted as of Early Jurassic

**Figure 5.** Upper Triassic–Lower Jurassic generalized stratigraphy of the southern (Holser et al., 1988), central (COST No. G-2 well of the Georges Bank platform, OERA, 2015; Mohican I-100 and Glooscap C-63 wells of the Scotian Basin, Weston et al., 2012 and MacRae et al., 2014; Eurydice P-36 well of the Orpheus Basin, this study), and northern (Holser et al., 1988) segments of the eastern North American rift system (ENARS). Refer to Figure 1 for segment locations. Fm—formation.
The Eurydice P-36 well penetrated ~600 m of the Eurydice Formation in the Orpheus Basin and collected core from its lowermost 9 m (Figs. 1C and 4). Palynological analysis date the Eurydice Formation as Rhaetian–Hettangian and the overlying Argo Formation as Hettangian–Sinemurian (Bujak and Williams, 1977; Barss et al., 1979). However, no age diagnostic palynomorphs were recovered from the studied core (Barss et al., 1979). Given its stratigraphic position 600 m below the top of Eurydice Formation and the lack of a definitive age assignment, it is assumed here that the studied core is of Rhaetian age.

The Mohican I-100 well penetrated ~90 m and recovered ~8.5 m of core from the Eurydice Formation in the Scotian Basin (Shell Canada Limited, 1972) (Figs. 1C and 4). A possible specimen of the Norian to Rhaetian dinocyst Rhaetogonyaulax cf. arctica was found in core #9 from well Mohican I-100 (Weston et al., 2012) (Figs. 1B and 4). As pointed out by Weston et al., if the dinocyst specimen was recovered in situ, it would indicate intermittent normal marine conditions in the Upper Triassic (Weston et al., 2012). Given that the core was stratigraphically collected above a salt unit, and if the argument holds true that Late Triassic salt is non-marine in origin (Holser et al. 1988; MacRae et al., 2014), then this core, in addition to the core from well Eurydice P-36, would contain the earliest evidence of marine incursion into the Scotian and Orpheus basins, as interpreted here.

Given the newly identified tidal deposits (assumed of Rhaetian age) coupled with the dinocyst finding, we suggest that this study provides the first unambiguous indication of marine incursions into the central segment of the ENARS. The Eurydice Formation in the central segment of the ENARS is contemporaneous with the Argo Formation from the Grand Banks region of the northern segment of the ENARS (Fig. 5). Our sedimentological evidence from the central segment of the ENARS, although limited to ~20 m in a depositional unit that is many km thick, supports the Holser et al. (1988) geochemical argument for marine incursions during the Late Triassic in the northern segment of the ENARS (Fig. 5).

PALEOGEOGRAPHIC IMPLICATIONS

During the beginning of Late Permian (Sues and Olsen, 2015) to Middle to Late Triassic (Wade and MacLean, 1990; Olsen, 1997) rifting, Nova Scotia was juxtaposed to Morocco, adjacent to Iberia and Newfoundland, west of the encroaching Tethyan sea, and at latitude 25° approximately (Wade and MacLean, 1990; Leleu et al., 2016). By at least the beginning of the Carnian, active rifting in large areas of Central Pangea (i.e., Iberia, England, eastern North America, and northwest Africa) had begun, which led to the inevitable opening of the Central Atlantic Ocean during the Early Jurassic (Labails et al., 2010). The westward encroachment of the Tethyan domain into the CAM has been well documented by progressive occurrences of Triassic marine indicators in eastern Iberia (Orti et al., 2017), Tunisia and northeast Morocco (Courcel et al., 2003), southern and western Iberia (Palain, 1976; Soares et al., 2012; Arche and Lopez-Gomez, 2014), offshore Newfoundland (Holser et al., 1988), and northwest Morocco (Et-Touhami, 2000). Inferences to Triassic marine incursion into the basins of Nova Scotia have been proposed (Jansa et al. 1980; McAlpine, 1990; Dercourt et al. 2000; Leleu et al., 2016; Orti et al., 2017) but no agreement has been reached on their validity. The westward movement of the Tethys through the Iberian domain and into the offshore regions of Newfoundland and eastern Morocco was the result of two main controls: global scale sea-level (eustatic) oscillations, and alternating periods of rift reactivation (uplift) and subsidence (Leleu et al., 2016; Orti et al., 2017). When combined, these controls played a major role in evaporite formation, leading to repeated episodes of restriction and to high sedimentary thickness (Orti et al., 2017).

Triassic marine incursions into the basins east of the Nova Scotia are evident. In CAM’s immediate vicinity and along the Iberian margins (Lusitanian and Algarve basins of western Iberia, Figure 1B, and multiple basins of eastern Iberian, northwest Morocco, and Tunisia), the Upper Triassic includes several marginal marine successions comprising evaporitic and dolomitic sediments, reflecting the gradual opening of these basins to an open marine environment (e.g., Palain, 1976; Courel et al., 2003; Soares et al., 2012; Arche and Lopez-Gomez, 2014). In Western Europe and the North Atlantic region, the Rhaetian witnessed progressive periodic incursions of marine waters from the Tethys Ocean, which flooded Norian lacustrine playas (e.g., Hounslow et al., 2012; Orti et al., 2017). Arche and Lopez-Gomez (2014) and Orti et al. (2017) have proposed Triassic marine connections of the Tethyan domain into south-central Europe, south-western Iberia, and northwestern Morocco via the Maghrebian-Gibraltan and the Bay of Biscay rift systems.

In the Atlas region of Morocco, Late Triassic marine incursions are ambiguous. For example, the Middle Anisian red beds of the Ramuntcho Siltstone Formation were once thought to be marine in origin based on possible in situ marine fossils and interpreted tidal sedimentary structures (e.g., Beauchamp, 1988). However, more recent interpretations of the unit suggest they were more likely to have been deposited in a continental setting (El Arabi et al., 2006). Mader et al. (2017) suggest that the southwesternmost basins of Morocco (Essaouira and Argana) likely had had no marine input until after the Carnian and possibly as late as the Earlist Liassic. However it remains open to discussion whether the term playa (continental dry depression) or sabkha (marine saline flats) is appropriate, as the exact nature of the shoreline could not be distinguished during their study.

Based on geochemical evidence (Br content), Holser et al. (1988) divided the Upper Triassic Moroccan evaporites into two groups, the Atlas and Atlantic provinces, reflecting non-marine and marine deposition, respectively. The salt units from the High Atlas province (mostly corresponding to the Atlas basins, Fig. 1B) were deposited in local continental playas or sabkhas fed by nonmarine waters. In contrast, the salt formations from the Atlantic province (offshore and northern areas of Morocco, Fig. 1B) indicate deposition in marginal marine basins, with significant nonmarine input. Et-Touhami’s (2000) geochemical dataset suggests that the Upper Triassic salt units from the Khémisset Basin (bordering the Moroccan Meseta and belonging to the Atlantic province of Holser et al., 1988) were deposited during alternate periods of continental and marine influence. Courel et al. (2003) suggested that severe basin subsidence, and possible fracturing in basin troughs, could have induced base-level variations and resulted in episodic connections between the Tethyan marine domain, the Khémisset Basin, and possibly more distal basins of offshore Morocco.

In the western portion of CAM (Scotian margin, offshore Nova Scotia), little is known regarding the depositional environments during the Late Triassic. Geochemical evidence (Br content) from MacRae et al. (2014) observed that Late Triassic salt at well Glooscap C-63 is probably continental in origin (low Br content). Based on the paleogeography, Leleu et al. (2016) suggests that any marine incursion would have been extremely extensive, and less likely, as there is no evidence for a coeval shoreline within 1000 km of the offshore region. However, given the lack of good quality data due to the depth of burial of these Triassic basins, and limited and scattered exploration wells in the margin, the occurrence of Triassic marine incursion should not be discounted. Deptuck and Kendall (2017) suggested that Eurydice Formation clastics were probably deposited in fluvial or lacustrine settings under hot and arid conditions, similar to
equivalent sediments of the Fundy Basin (Jansa and Wade, 1975), but the lateral changes in lithofacies and depositional environments remains largely unknown when moving toward the axial rift zone. Leleu et al. (2016) put forward the idea that the occurrence of thick salt deposits could indicate larger subsidence and extension rates in the Scotian margin, which may have facilitated seawater incursion. Given that the offshore region of Nova Scotia likely experienced pulses of tectonic activity (ripping and subsidence) and that the fault system of the Orpheus Basin (Minas Fault Zone, after Keppie, 1982) was oriented near parallel to the Maghrebian-Gibraltar, it could be proposed that intermittant marine incursion entered the central ENARS via this fault system pathway. However, limited offshore data restricts definitive evidence of this. Taking into consideration (i) the Rhaetian tidal deposits here identified in the Scotian and Orpheus basins, (ii) the Norian–Rhaetian dinocyst found in core 9 of the Mohican I-100 well (Weston et al., 2012), and (iii) the Br data from Holser et al. (1988) and Et-Touhami (2000) suggesting a marine origin for the Upper Triassic evaporites in the northern segment of the ENARS and offshore and northern areas of Morocco, it is clear that the CAM witnessed widespread marine ingression during the Late Triassic (Fig. 5). Our study elucidates that the two hypotheses presented by Leleu et al. (2016) for the paleogeographical reconstruction of the CAM during the Rhaetian, marine vs non-marine influence in the ENARS during the Upper Triassic, are not mutually exclusive. As the data from Et-Touhami (2000) suggest, continental versus marine influence deposited alternate during the Upper Triassic in the African CAM margin. Although the Rhaetian corresponds to a eustatic low (e.g., Haq et al., 1987), in the ENARS these periods of marine ingestion were most likely contemporaneous with the transgressive phase of the T-R facies cycle T4 defined for Western Europe (e.g., Giauola and Jaquicq, 1998).

CONCLUSIONS

In the Scotian and Orpheus basins of the northern CAM, two cores of assumed Rhaetian age from the Eurydice Formation (Rhaetian–Lower Hettangian) contain sediments with evidence of tidal processes, most likely occurring in a marine-influenced estuarine or deltaic environment. Our investigation provides the first sedimentological evidence of Late Triassic–Early Jurassic marine ingression into the central segment of the ENARS (northern margin of the CAM), most likely contemporaneous with regional transgressive events recorded in Western Europe. However, it is recognized that the conclusions of this study are drawn from less than 20 m of core retrieved from a unit that is km in thickness, so it is wise to emphasize that the variability of environments during this part of the Late Triassic are still very poorly understood.

Our findings challenge the concept of a linear evolution of the CAM basins during the Triassic–Lower Jurassic; instead deposition seems to be punctuated by marked and recurring changes from marine and non-marine environments. Our findings have far reaching implications for the understanding of Triassic paleogeography and paleoclimates, biological evolution, and current resources exploration.

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