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# From freshwater to fully marine: Exploring animal-substrate interactions along a salinity gradient (Miocene Oficina Formation of Venezuela)

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ABSTRACT

Venezuela has the largest hydrocarbon reserves in the world and most of these are within the Orinoco Oil Belt. The Oficina Formation of the Orinoco Oil Belt and the Oritupano Field comprises a wide range of environments formed under variable salinity conditions. These include freshwater fluvial and fluvio-tidal transition zones, brackish-water estuarine and delta-plain segments, alternating brackish-water and near-normal marine delta-front and prodelta settings, and normal-marine wave-dominated shoreface and offshore-shelf environments. The Oficina Formation thus provides an ideal opportunity to evaluate trace-fossil distribution and ichnofacies gradients along a depositional profile and to calibrate salinity-related trace-fossil models. The Oficina Formation contains four softground ichnofacies (*Scoyenia*, depauperate *Cruziana*, *Skolithos*, and archetypal *Cruziana*) and two substrate-controlled ichnofacies (*Teredolites* and *Glossifungites*). Fluvial deposits in freshwater portions of tide-influenced, estuarine channels and distributary channels of tide-dominated deltas are locally intensely bioturbated, displaying low-diversity occurrences of the *Scoyenia* Ichnofacies. Brackish-water delta-plain and estuarine deposits display lower degrees of bioturbation and low ichnodiversity, as revealed by depauperate *Cruziana* Ichnofacies and the *Skolithos* Ichnofacies. Wave-dominated deltaic deposits display the *Skolithos* and the depauperate *Cruziana* Ichnofacies, but the presence of some ichnotaxa (*e.g.*, *Chondrites*) suggests periods of lower salinity stress, probably during times of reduced freshwater discharge. Open-marine deposits are characterized by intense bioturbation and very high diversity, as shown by the archetypal *Cruziana* Ichnofacies in low-energy distal settings, whereas high-energy proximal settings are characterized by the *Skolithos* Ichnofacies. Faunal distribution is strongly controlled by salinity, which makes trace-fossil evidence particularly useful for paleoenvironmental characterization of marginal-marine systems. In addition, the *Glossifungites* and *Teredolites* Ichnofacies indicate erosional exhumation of marginal-marine deposits, outlining transgressive surfaces of erosion. The Oficina Formation shows remarkable similarities in sedimentary facies and both trace-fossil and micropaleontological content with the Cretaceous McMurray Formation of western Canada.

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## 1. Introduction

Marginal-marine depositional systems, such as estuaries and deltas, have been subjected to increased scrutiny from an ichnologic perspective during the last three decades (*e.g.*, Pemberton et al., 1982; Pemberton and Wightman, 1992; MacEachern and Pemberton, 1994; Buatois et al., 1997a, 2008, 2012; Buatois et al., 2011; Mángano and Buatois, 2004; MacEachern et al., 2005; MacEachern and Gingras, 2007; Gingras et al., 2012, 2016; Dasgupta et al., 2016). In fact, trace fossils have become valuable tools to identify marginal-marine deposits and to delineate their subenvironments within a robust depositional and sequence-stratigraphic framework (*e.g.*, MacEachern and Pemberton, 1994). Marginal-marine environments are typified by rapid salinity changes, increased sediment discharge, high water turbidity and extreme clay flocculation, among many other controlling factors (see Buatois and Mángano, 2011, and references therein). This characteristically results in stressful environmental conditions that play a major role in controlling the response by the benthos and their interactions with the substrate, imparting detectable signals in the trace-fossil record. However, there are still few studies that document animal-substrate interactions within a single stratigraphic unit along extensive salinity gradients, from freshwater to brackish water and normal-marine salinity conditions (*e.g.*, Mángano and Buatois, 2004). Such studies are essential to calibrate stressed trace-fossil suites against those of fully marine conditions (Buatois et al., 2005).

The Miocene Oficina Formation of the Orinoco Oil Belt and the Oritupano Field in Venezuela (Fig. 1A–C) comprises a wide range of

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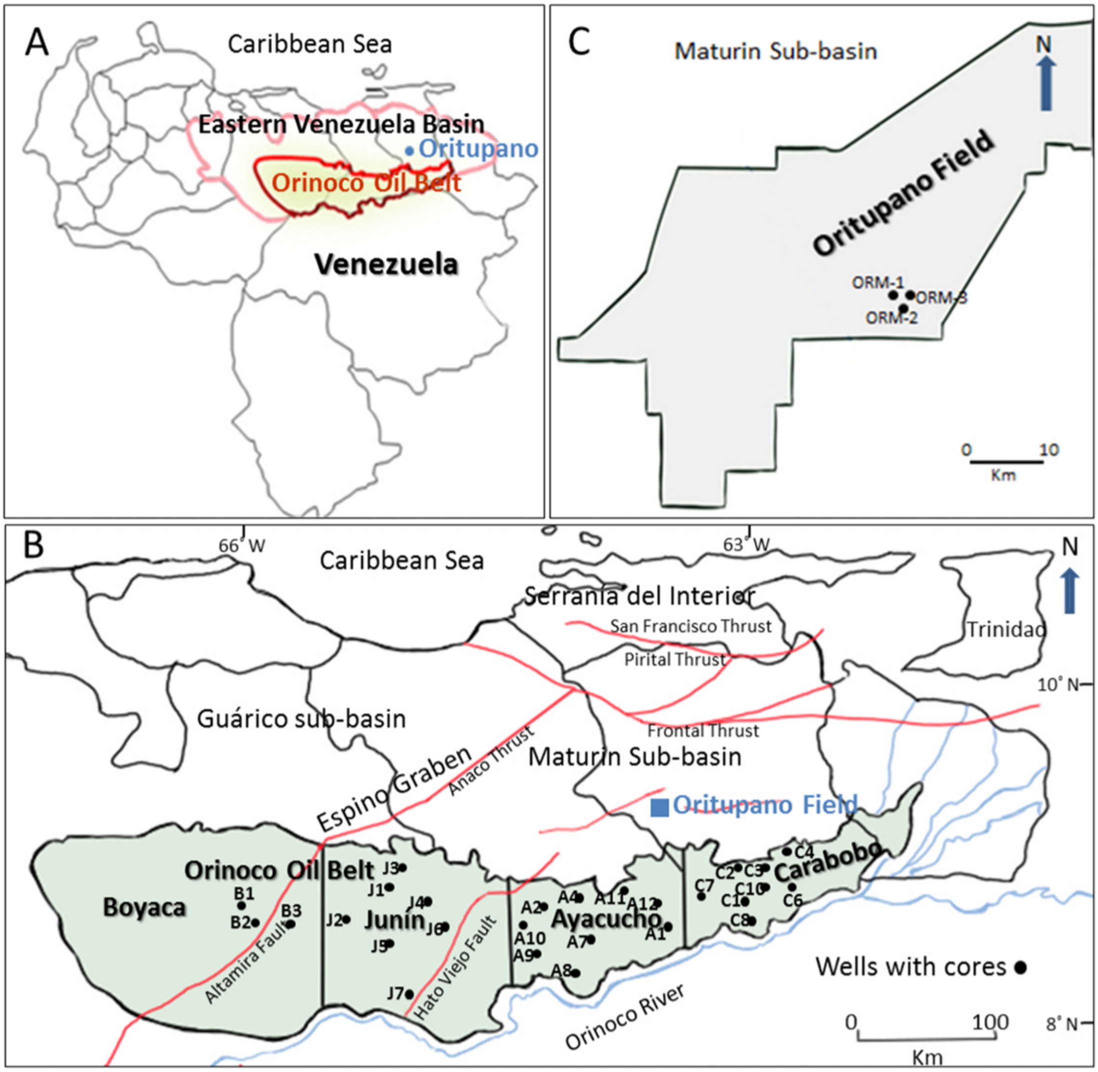


**Fig. 1.** Location Map of the study areas. A) Map of Venezuela showing the location of the Eastern Venezuela Basin, outlining the Orinoco Oil Belt, and the Oritupano Field. C) Map of the Oritupano Field. B) Map of the Orinoco Oil Belt and the main associated structural features.

depositional environments formed under variable salinity conditions. These include freshwater fluvial and fluvio-tidal transition zones, brackish water estuarine and delta-plain settings alternating brackish-water and near-normal marine in delta-front and prodelta settings, and normal-marine shoreface and offshore-shelf environments. Therefore, this unit provides an ideal opportunity to evaluate trace-fossil distribution and ichnofacies gradients along a depositional profile. In the specific case of the Oficina Formation, refinement of paleoenvironmental reconstructions is essential because this unit hosts one of the largest hydrocarbon reservoirs in the world. The aims of this paper are to: (1) document animal-substrate interactions in different subenvironments of the Oficina Formation, (2) discuss how the pattern emerging from the analysis of this unit compares with the currently accepted models of marginal-marine depositional systems, and (3) compare our observations with those in similar deposits of the Cretaceous McMurray Formation of western Canada, whose interpretation have been subject to debate recently.

## 2. Geologic setting

The Eastern Venezuela Foreland Basin formed during the Neogene on the passive margin of the South American Craton is composed of several petroleum fields; two of these are the Orinoco Oil Belt and the Oritupano area (Fig. 1A). This foreland basin is subdivided by the Anaco-Altamira fault system into the Maturin and Guárico sub-basins (Fig. 1B).

The Orinoco Oil Belt spans an area of 55,315 km$^2$ in the southern margin of the Eastern Venezuela Basin, sub-parallel to the Orinoco River (Fig. 1B). The Hato Viejo fault system subdivides the Orinoco Oil Belt into two provinces, the western and eastern provinces (Latreille et al., 1983; Audemard et al., 1985). The western province is located west of the Hato Viejo fault system and consists of the Boyaca and Junín areas where the Cenozoic succession unconformably overlies Cretaceous and Paleozoic strata. The eastern province is located east of the Hato Viejo fault system, and includes the Carabobo and Ayacucho areas, where the Cenozoic succession rests on top of the Precambrian basement. The Oritupano Field is located northeast of the Orinoco Oil Belt in the Maturin sub-basin (Fig. 1B and C).

Based on an integrated analysis of foraminifers, calcareous nanoplankton and palynomorphs, the Oficina Formation is considered of middle Miocene age (Audemard et al., 1985; Solórzano et al., 2015) and spans the Langhian Stage, and the Serravallian Stage (Fig. 2). Three third-order depositional sequences and three maximum flooding surfaces were identified in the Oficina Formation. These maximum flooding surfaces can be correlated throughout the Eastern Venezuela Basin (Campos et al., 1985; Giffuni et al., 2000; Flores et al., 2001) and the Orinoco Oil Belt (Latreille et al., 1983; Audemard et al., 1985; Solórzano and Farías, 2016).

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