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PALEOICNOLOGIA DE DEPÓSITOS TURBIDÍTICOS: UM ESTUDO DA FORMAÇÃO CAPDEVILA, EOCENO INFERIOR, CUBA OCIDENTAL

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PALEOICNOLOGIA DE DEPÓSITOS TURBIDÍTICOS: UM ESTUDO DA FORMAÇÃO CAPDEVILA, EOCENO INFERIOR, CUBA OCIDENTAL

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RESUMO

Os estudos icnológicos na Formação Capdevila são escassos e são conhecidos apenas alguns trabalhos nos quais os autores identificaram icnotaxonomicamente os traços fósseis. A presente contribuição tem como objetivos identificar e estudar os icnofósseis da Formação Capdevila para realizar uma interpretação paleoecológica mais detalhada de seus depósitos. Para isto, foi estudado material depositado em coleções e descrito em um afloramento da Formação Capdevila (Bacia Los Palacios, Cuba ocidental). Foram identificados traços atribuídos a *Bichordites* e variadas morfologias preservacionais de *Scolicia.* Foram reconhecidas nove icnofábricas (*Asterosoma, Thalassinoides, Palaeophycus, Scolicia. Bichordites-Thalassinoides, Rhizocorallium, Scolicia-Thalassinoides, Ophiomorpha* e *Raízes*) ao longo da sucessão estudada, em fácies de arenitos maciços e arenitos com laminação plano-paralela. Esta icnofauna representa baixa icnodiversidade, predomínio de organismos sedimentívoros, condições marinhas de salinidade e boa oxigenação do substrato. A integração das análises sedimentológica e icnológica da sucessão permitiu propor uma deposição em um talude pouco profundo, impactado por frequentes fluxos gravitacionais e/ou alta frequência deposicional. As suítes identificadas são correspondentes às icnofácies Glossifungites, Cruziana e Skolithos, sendo as duas últimas atípicas se comparadas com suas equivalentes arquetípicas, como resultado do estresse causado pelo predomínio de condições de alta energia e/ou alta frequência deposicional. Estas suítes indicam, para a seção estudada, processos de raseamento destes depósitos até um período de exposição subaérea, marcado por um evento de regressão forçada, e o restabelecimento posterior de condições marinhas, com a subida do nível de base.

PALAVRAS CHAVE: Icnofósseis. Turbiditos. Paleoecologia. Formação Capdevila. Bacia Los Palacios. Cuba ocidental.

ABSTRACT

Ichnological studies in Capdevila Formation (Los Palacios Basin, Lower Eocene) are scarce and there are few works in which the authors just identified the taxa of the trace fossils. The aims of this work are identify and study the ichnofossils from Capdevila Formation in order to realize a more accurate paleoecological interpretation of these deposits. Thus, samples from a fossil colection and from an outcrop of Capdevila Formation (Western Cuba) were studied. Trace fossils assigned to *Bichordites* and varied preservational morphologies of *Scolicia* were identified. Nine ichnofabrics (*Asterosoma, Thalassinoides, Palaeophycus, Scolicia. Bichordites-Thalassinoides, Rhizocorallium, Scolicia-Thalassinoides, Ophiomorpha* and *Root traces*) were recognized along the succession, preserved both in massive sandstone and sandstone with parallel lamination. This ichnofauna represents low ichnodiversity, dominance of sediment feeders, marine salinity conditions and a well-oxigenated substrate. The integrate sedimentological / ichnological analysis of the succession allowed to propose a depositional model of shallow slope, impacted by frequent gravity flows and / or high depositional rate. The recognized suites correspond to Glossifungites, Cruziana and Skolithos ichnofacies, being the latter two atypical when compared with their arquetipical counterparts, as a result of the stress caused by the predominance of high-energy conditions and / or high depositional rate. These suites indicate, for the studied succession, a shallowing phase of these deposits, including a period of subaerial exposure marked by a forced regression event, and the subsequent reestablishment of marine conditions, with the base level rise.

KEY WORDS: Ichnofossils. Turbiditic. Paleoecology Capdevila Formation. Los Palacios Basin. Western Cuba.

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SUMARIO

1. INTRODUÇÃO

Os icnofósseis são um grupo de reconhecimento relativamente recente do ponto de vista taxonômico. Seu estudo nos últimos anos tem alcançado uma maior importância, já que a Icnologia é amplamente reconhecida como uma ciência interdisciplinar (Vitaned & Liñán 1996), pois além da paleontologia sistemática, fornece importantes dados para as reconstruções paleoecológicas e paleoambientais, a sedimentologia e a estratigrafia (Meléndez 1989; Buatois *et al.* 2002; Buatois & Mángano 2011). Além disso, os icnofósseis proporcionam uma rica informação sobre a presença de numerosas espécies, muitas das quais não deixaram restos corpóreos no registro fóssil (Martínez & Santoja 1994; Fernandes *et al.* 2007).

A pesar de sua grande utilidade, estudos icnológicos em Cuba são escassos e na literatura geológico-paleontológica os icnofósseis são tratados em sua maioria sob termos gerais ou ambíguos como: “bioglifos”, “hieróglifos”, “trilhas”, "canais", “bioturbação” ou “bioerosão” (*e.g.*, Jakus 1983, Albear & Iturralde-Vinent 1985, Piotrowski 1987, Pszczółkowski 1987, Rojas-Consuegra 1999). Existem apenas alguns estudos pontuais onde são identificadas e descritas estas estruturas biogênicas (Pszczółkowski 2002, Pszczółkowski & Myczynski 2009, Villegas-Martín & Rojas-Consuegra 2011, Menéndez-Peñate *et al.* 2011, Villegas-Martín *et al.* 2012). Na maioria desses trabalhos os icnofósseis foram identificados de maneira isolada, sem vinculação com as fácies sedimentares e, portanto, não foram utilizados para interpretar variações nos parâmetros paleoecológicos e paleoambientais.

A Formação Capdevila, que contém a sucessão objeto deste estudo, tem apenas um registro icnológico conhecido (Brönnimann & Rigassi 1963), mas tem ampla variedade de material depositado em coleções (Villegas-Martín 2009, Villegas-Martín & Rojas-Consuegra 2008, 2010), além de outros exemplares observados e reportados em afloramentos (Brust *et al.* 2011). Um estudo icnológico pode dar uma ideia da comunidade bentônica existente, assim como as variações de alguns parâmetros ecológicos vigentes no momento da deposição dos sedimentos. A posterior vinculação com as fácies sedimentares resultaria em uma caracterização paleoambiental mais detalhada de seus depósitos.

1.1 Objetivos

(a) Identificar e descrever os icnofósseis da Formação Capdevila com base nos critérios icnotaxonômicos atuais.

(b) Reconhecer as associações de fácies e as associações de icnofósseis presentes na sucessão.

(c) Analisar de maneira integrada as associações de fácies e a icnofauna para realizar inferências paleoecológicas e paleoambientais.

1.2. Organização da tese

A presente tese de mestrado está composta pelos seguintes itens: introdução, contexto icnológico e geológico, materiais e métodos, resultados e discussões, conclusões e considerações finais. No item Contexto icnológico-geológico é apresentada uma síntese dos trabalhos onde foram identificados icnofósseis nas rochas cubanas e são descritas as principais características da Bacia Los Palacios e da Formação Capdevila. Materiais e métodos estão estruturados com aspectos gerais sobre a área de estudo, dados utilizados neste trabalho e os principais métodos e classificações seguidas em cada caso. As informações mais detalhadas em relação à metodologia podem ser encontradas em cada um dos artigos no item resultados e discussões. Os resultados obtidos neste trabalho são compilados à maneira de três artigos científicos. No começo do item é indicada a informação geral de seu conteúdo e sua importância frente aos objetivos propostos.

2. CONTEXTO ICNOLÓGICO

Nos estudos paleontológicos cubanos, existem escassos trabalhos sobre icnologia, predominando os registros de icnofósseis de invertebrados sobre aqueles de vertebrados

2.1. Registro de traços fósseis de invertebrados

Um dos primeiros trabalhos de identificação icnotaxonômica de icnofósseis de invertebrados em Cuba foi realizado por Brönnimann & Rigassi (1963), que identificaram traços atribuídos ao icnogênero *Chondrites* na Formacão Capdevila (Eoceno) na província de La Habana, Cuba ocidental (Tabela 1), mas os traços são apenas mencionados e não descritos. Outro trabalho com esta temática foi apresentado por Segura-Soto (1990) em um evento do Instituto de Geología y Paleontología, onde o autor falou sobre a utilidade da classificação etológica dos icnofósseis.

Nas menções gerais a icnofósseis, cabe destacar as realizadas por Rojas-Consuegra (2004), que observou estruturas de bioerosão sobre conchas de várias espécies de moluscos (rudistas) da formação Jimaguayú do Cretáceo cubano e por López-Martínez (2006), que registrou estruturas semelhantes em gastrópodes do Mioceno da Formação Lagunitas, a qual atribui à ação bioerosiva de poliquetas.

Neste período, foi publicado o que se pode considerar como trabalho pioneiro na icnologia cubana, realizado pelo geólogo polonês Pszczółkowski (2002), que descreveu na formação Vaquería (Cretáceo), na região central de Cuba, galerias predominantemente horizontais de 30 a 50 cm de comprimento. Em sua maioria, possuíam bifurcação dicotômicae e presentavam interseções em forma de T. Eram circulares a elipsoidais em seção transversal e foram associadas pelo autor ao icnogênero *Thalassinoides*. Pszczółkowski & Myczynski (2009) identificaram na Formação Guasasa (Jurássico), em Cuba ocidental, galerias horizontais que associaram aos icnogêneros *Chondrites* e *Planolites,* mas sem aplicar um tratamento icnotaxonômico profundo.

Nos últimos anos, vem sendo realizados estudos preliminares no país, principalmente na forma de apresentações em eventos, para desenvolver e popularizar a icnologia, os quais tem possibilitado um pequeno aumento no conhecimento icnotaxonômico. Nesse contexto, foram identificadas estruturas de bioerosão associadas a *Entobia*, *Oichnus* e *Centrichnus* em moluscos gastrópodes e bivalves do Mioceno, redepositados em sedimentos lateríticos em Moa, Cuba oriental (Villegas-Martín 2009). Em rochas originadas por fluxos turbidíticos, foram identificadas estruturas de bioturbação sobre arenitos das formações Capdevila e Vertientes (Eoceno), assinaladas aos

Tabela 1. Síntese dos icnofósseis encontrados nos depósitos cubanos, contendo formação geológica, idade e referência.

Icnogêneros	Formação Geológica	Idade	Referências
Chondrites *Palnolites*	Guasasa	Jurássico	Pszczółkowski & Myczynski (2009)
Teredolites	Jagua	Jurássico	Villegas-Martín *et al.* (2012)
Thalassinoides *Chondrites*	Vaquería Provincial	Cretáceo	Pszczółkowski (2002) Villegas-Martín *et al.* (2011)
Teredolites	Peñalver	Limite K/Pg	Villegas-Martín & Rojas-Consuegra (2011)
Chondrites	Nazareno	Eoceno	Villegas-Martín *et al.* (2011)
Chondrites	Capdevila	Eoceno	Brönnimann & Rigassi (1963)
Scolicia *Planolites* *?Psammichnites* *Taenidium* *Helmintorhaphe* *Cosmorhaphe*	Capdevila	Eoceno	Villegas-Martín & Rojas-Consuegra (2010) Villegas-Martín & Rojas-Consuegra (2008) Villegas-Martín (2009)
?Ophiomorpha *Cosmorhaphe*	Vertientes	Eoceno	Villegas-Martín & Rojas-Consuegra (2010)
Planolites *Entobia*	Vertientes	Eoceno	Menéndez-Peñate*et al.* (2011)
Entobia *Oichnus* *Centrichnus*	Sedimentos lateríticos	Mioceno	Villegas-Martín (2009)

icnogêneros *Scolicia*, *Planolites*, *Cosmorhaphe* e *Taenidium* (Villegas-Martín& Rojas-Consuegra 2008, 2010).

Foi reconhecida também a presença de traços associados ao icnogênero *Chondrites* nas formações Nazareno (Paleógeno) e Provincial (Cretáceo), região central de Cuba (Villegas-Martín 2009, Villegas-Martín *et al*. 2011).

Em trabalhos publicados Menéndez-Peñate *et al*. (2011) identificaram, em um estudo paleontológico realizado na Formação Vertientes, uma galeria horizontal preservada em um arenito, que atribuíram tentativamente ao icnogênero *Planolites*, além de estruturas de bioerosão atribuídas ao icnogênero *Entobia.* Posteriormente, Villegas-Martín & Rojas-Consuegra (2011) reportaram a presença do icnogênero *Teredolites*, identificando as icnoespécies *T. clavatus* e *T. longissimus*, e analisaram sua presença em um fragmento de madeira preservado em um bloco composto por arenitos e lamitos na formação Peñalver (limite K/Pg), em Cuba ocidental. Posteriormente, este mesmo icnogênero foi reconhecido por Villegas-Martín *et al*. (2012) em fragmentos de madeira preservados em concreções carbonáticas atribuídas a moluscos bivalves da Formacão Jagua (Jurássico Superior) em Cuba ocidental.

2.2 Registro de traços fósseis de vertebrados

Não existem trabalhos focados em traços fósseis de vertebrados em Cuba, apenas foram encontradas duas menções gerais na literatura. A primeira e tal vez a mais antiga corresponde à possível trilha deixada pela garra de uma preguiça (*Megalocnus*), em uma caverna de San Antonio, em Cuba ocidental (Fernándes de Castro 1864). A outra menção foi feita por Rojas-Consuegra (1999), que observou prováveis trilhas de vertebrados nos carbonatos do arco cretáceo. Em ambos os casos, é necessário realizar estudos para comprovar a verdadeira origem das estruturas. Ainda sobre traços fósseis deste tipo, também foram reportadas no país estruturas de biodeposição (coprólitos) produzidas por vertebrados, no entanto os trabalhos são escassos e na maioria dos casos se restringem à descrição superficial (forma e dimensões) das amostras (Arredondo &Villavicencio 2004, Jiménez *et al*. 2005).

3. CONTEXTO GEOLÓGICO

3.1. Bacia Los Palacios

A Bacia Los Palacios está localizada ao sul da falha Pinar, na porção ocidental de Cuba (Figura 1) e é formada por sedimentos sin-e pós-orogênicos (Maastrichtiano–Eoceno) derivados de seções de terras emersas. Atualmente, o relevo desta bacia é plano e seus depósitos são principalmente paleógenos e neógenos, mas comporta sedimentos depositados do Cretáceo Superior (Maastrichtiano) ao Quaternário (Brust *et al.* 2011).

Os estudos estratigráficos (Piotrowski 1987, Bralower & Iturralde 1997) apontam que o preenchimento da bacia começa com a deposição da Formação San Juan y Martinez (calcário com moluscos rudistas, arenitos e conglomerados em menor quantidade depositados em um ambiente marinho costeiro) (Figura 1), fracamente afetada por atividade tectônica. Sobre estes depósitos, se assentam de forma discordante os do Grupo Víbora (Paleoceno Superior), constituídos por calizas margosas, arenitos finos e conglomerados, indicando uma profundização da bacia. Cobrindo os depósitos desta idade pode aparecer uma estrutura em *gap* e, logo após, a deposição de sedimentos siliciclásticos de granulometria grossa e de sedimentos carbonáticos (arenitos calcáreos) sob condições predominantemente marinhas, caracterizam a Formação Capdevila (base do Eoceno Inferior). Piotrowski (1987) propõe que, durante o Eoceno, a bacia esteve afetada por forte incremento da atividade tectônica, que originou um razeamento e posteriormente se estabilizou, dando lugar à deposição de margas hemipelágicas que caracterizam a Formação Universidad (topo do Eoceno Inferior). Um hiato ocorre entre esta última e a Formação Loma Candela (Eoceno Médio), caracterizada pela sedimentação de conglomerados, calizas, margas arenosas e arenitos (Piotrowski 1987).

Várias alternativas foram propostas para explicar este aumento na atividade tectônica durante o Eoceno, atribuindo-o a movimentos orogênicos nas montanhas de Guaniguanico e a movimentos de blocos ao largo da falha Pinar durante o Eoceno Inferior (Piotrowski 1987, Bralower & Irurralde-Vinnent 1997, Gordon *et al.* 1997). A Bacia Los Palacios é considerada do tipo *piggiback* e *strike-slip* (Iturralde-Vinent 1995, 1996, Sommer 2009, Brust *et al.* 2011). Foi proposto que a área fonte dos sedimentos da bacia poderia ser uma área elevada localizada a NE da mesma (Brust *et al.* 2011).

3.2. Formação Capdevila

3.2.1. Localização e Idade

A Formação Capdevila tal como originalmente descrito por Palmer (1934) pertence ao Grupo Mariel, que inclui também as formações Mercedes, Apolo e Madruga. Seus depósitos afloram na região ocidental de Cuba (Figura 1) e têm um bom desenvolvimento nas províncias de La Habana, Artemisa e Pinar del Río (Brönnimann & Rigassi 1963; Albear & Iturralde-Vinent 1985).

Em Cuba, além da Bacia Los Palacios (Piotrowski 1987), a Formação Capdevila forma parte do preenchimento da unidade sedimentar-tectônica Bahía Honda, nas províncias de Artemisa e La Habana, e do anticlinal Havana-Matanzas na parte norte de La Habana e Matanzas (Albear & Iturralde-Vinent 1985, García-Delgado & Torres-Silva 1997, Figura 1B). Estas unidades se assentam sobre o topo do arco vulcânico cretáceo das Antilhas Maiores (Brust*et al.* 2011).

A Formação Capdevila é considerada de idade Eoceno Inferior (Bralower & Iturralde-Vinent 1997, Brust *et al.* 2011) por suas associações de foraminíferos, incluindo a espécie *Globorotalia palmerae* (Bröniman & Rigassi 1963; Brönnimann & Stradner 1960), e zonas de nanofósseis (zonas NP 11 e NP 12 de ODP Sitio 865, segundo Bralower & Iturralde-Vinent, 1997), incluindo a espécie *Marthasterite stribrachiatus* (Brönnimann & Stradner 1960). Nesta formação também foram reportadas associações microfaunísticas que a posicionaram em um intervalo que vai desde o Eoceno Médio até o Paleoceno Superiore outras típicas do Cretáceo Superior (Piotrowski 1987, De la Torre 1987, Brust*et al.* 2011), mas os autores mencionam a carência de caracteres diagnósticos para a maioria dos componentes destas microfaunas e de possíveis processos de retrabalhamento para explicar sua presença.

3.2. 2. Sedimentologia e interpretação dos depósitos

Não existem muitos trabalhos publicados sobre a sedimentologia da Formação Capdevila. Uma descrição detalhada da unidade foi realizada por Bröniman & Rigassi (1963), que definiram quatro unidades litológicas de composição mista para a formação na cidade de La Habana. Especificamente na Bacia Los Palacios, segundo Piotrowski (1987) e Brust *et al.* (2011), a Formação Capdevila é composta por arenitos, argilitos, siltitos, margas, carbonatos e conglomerados. Também foi apontada a presença de tufos e abundantes concreções carbonáticas nas camadas de arenitos finos e siltitos para esta unidade (Brönnimann & Rigassi 1963, Brust *et al.* 2011).

Os arenitos podem apresentar diferente granulometria (fina, meia, grossa) e podem constituir camadas maciças ou com estratificação plano-paralela. As camadas de conglomerados podem conter rochas vulcânicas, ígneas, metamórficas e carbonáticas e estas podem encontrar-se suportadas por matriz ou por arcabouço (Piotrowski 1987, Brust *et al.* 2011). Segundo Brust *et al.* (2011), os conglomerados suportados pela matriz são depósitos originados por fluxos de detritos e os suportados por arcabouço derivam de fluxos densos hiperconcentrados. As camadas de conglomerados e arenitos podem apresentar gradação normal ou inversa.

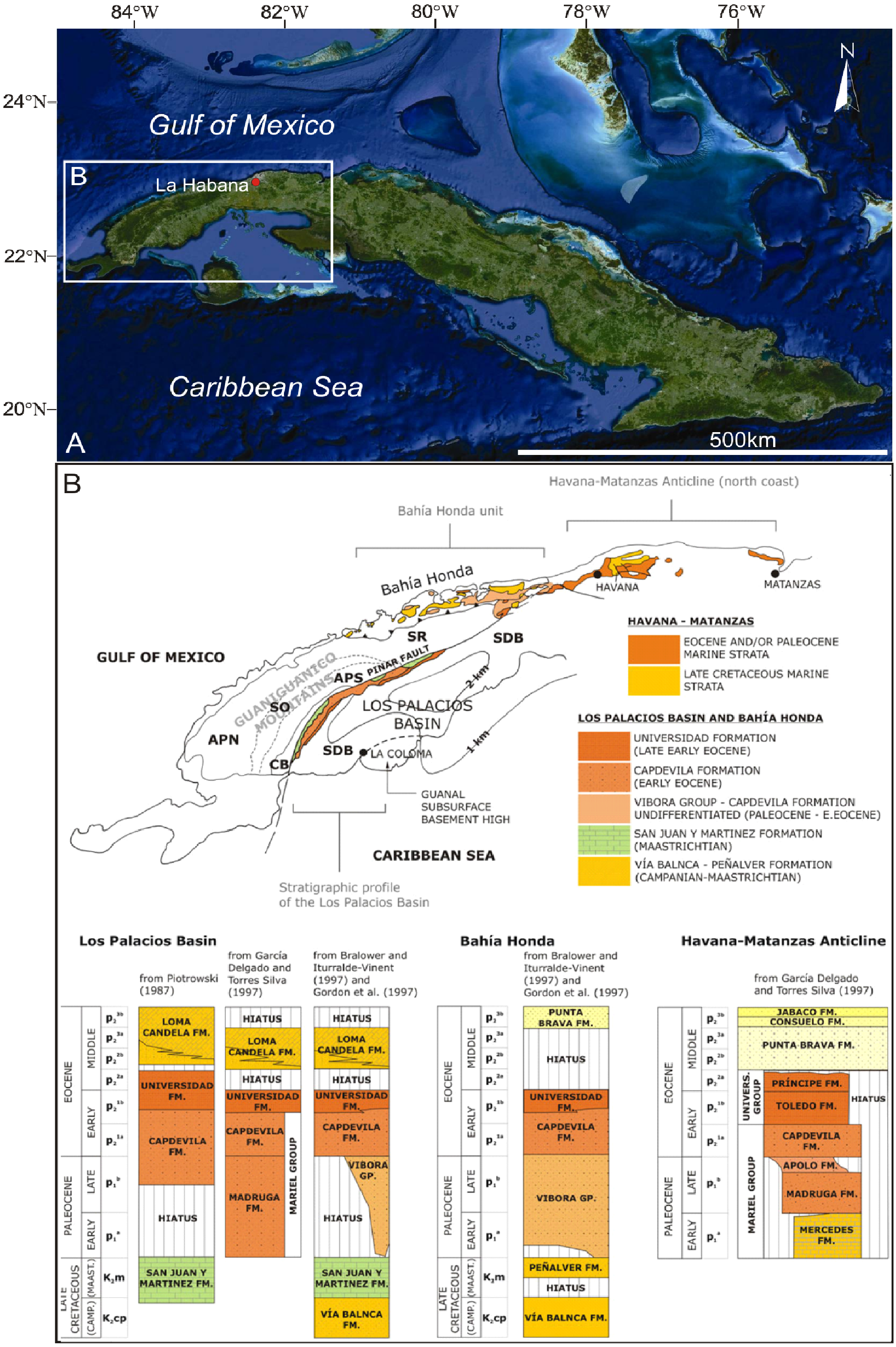

Figura 1. Distribuição geográfica (A) e estratigráfica (B) da Formação Capdevila na porção ocidental de Cuba. B a partir de Brust *et al*. (2011).

Foi proposto por Brust *et al.* (2011) que os sedimentos siliciclásticos mais grossos (conglomerados, areias) e os sedimentos carbonáticos (areias calcáreas) da Formação Capdevila (Eoceno Inferior), se depositaram sob condições marinhas durante uma fase de incremento da atividade tectônica no Eoceno.

Esta atividade tectónica foi muito investigada nas diferentes zonas mencionadas (Bacia Los Palacios, unidade tectônica de Bahía Honda e anticlinal Havana-Matanzas) e a ela foram atribuídas diferentes origens (Piotrowski 1987, Iturralde-Vinent 1995, 1996). Albear & Iturralde-Vinent (1985) registraram em algumas localidades da Formação Capdevila inclusões de várias dezenas de metros cúbicos constituídos por rochas de outras formações (Peñalver, Alkazar). Os autores propõem que estas rochas poderiam ser interpretadas como olistolitos ou tratar-se de blocos tectonicamente imbricados dentro da unidade. Esta atividade também é comprovada pela presença de clastos de rochas granitóides e clastos metamórficos (gneiss) (Pszczółkowski & Albear 1982). Em sucessões da Formação Capdevila foram encontrados sedimentos de plataformas carbonáticas que, segundo Brust *et al.* (2011), foram retrabalhados, misturados com materiais terrígenos e siliciclásticos e redepositados, posteriormente, devido à elevação tectônica, estes sedimentos teriam sido erodidos e redepositados em ambientes marinhos.

3.2.3. Fauna e Ambiente sedimentar

A fauna que tem recebido maior atenção nesta unidade é a de microfósseis, tendo sido reportada uma grande variedade de táxons (Cushman & Bermudez 1949; Brönnimann & Rigassi 1963; Piotrowski 1987; Brönnimann & Stradner 1960). Além desta microfauna, foi reportada a presença de abundantes traços fósseis, mas sem identificação icnotaxonômica (Brust *et al.* 2011), exceto por Brönnimann & Rigassi (1963), que registraram traços atribuídos ao icnogênero *Chondrites*, e os trabalhos do presente autor. Tambem foram encontrados bivalves, fragmentos de equinodermos, braquiópodos, fragmentos pequenos de plantas macroscópicas e corais (Amphiroa, Lithophyllum), assim como de solenoporos (Solenopora) e algas vermelhas (Brust *et al.* 2011). Muitos elementos desta biota, segundo Flügel (2004) e Brust (2006), são típicas associações de alta energia de ambientes marinhos rasos e foram apontados como material retrabalhado para esta formação.

A interpretação mais aceita para o ambiente deposicional da Formação Capdevila é um mar de profundidades batiais, durante uma fase de tectogênese ativa, onde grandes volumes de materiais terrígenos provenientes de terras emersas eran transportados por correntes de turbidez, dando origem à deposição de um típico *flysh* (Albear & Iturralde-Vinent 1985). Por outro lado, Brust *et al.*

(2011) propuseram uma deposição em talude para esta formação em Pinar del Río (Bacia Los Palacios).

4. MATERIAIS E MÉTODOS

4.1. Área do afloramento estudado

O afloramento estudado está localizada na região ocidental de Cuba, na província de Pinar del Río. A seção estudada pertence à Formação Capdevila, Bacia Los Palacios, e se encontra a 20 km da cidade de Pinar del Río, entre esta e a falha Pinar del Río (Figura 2).

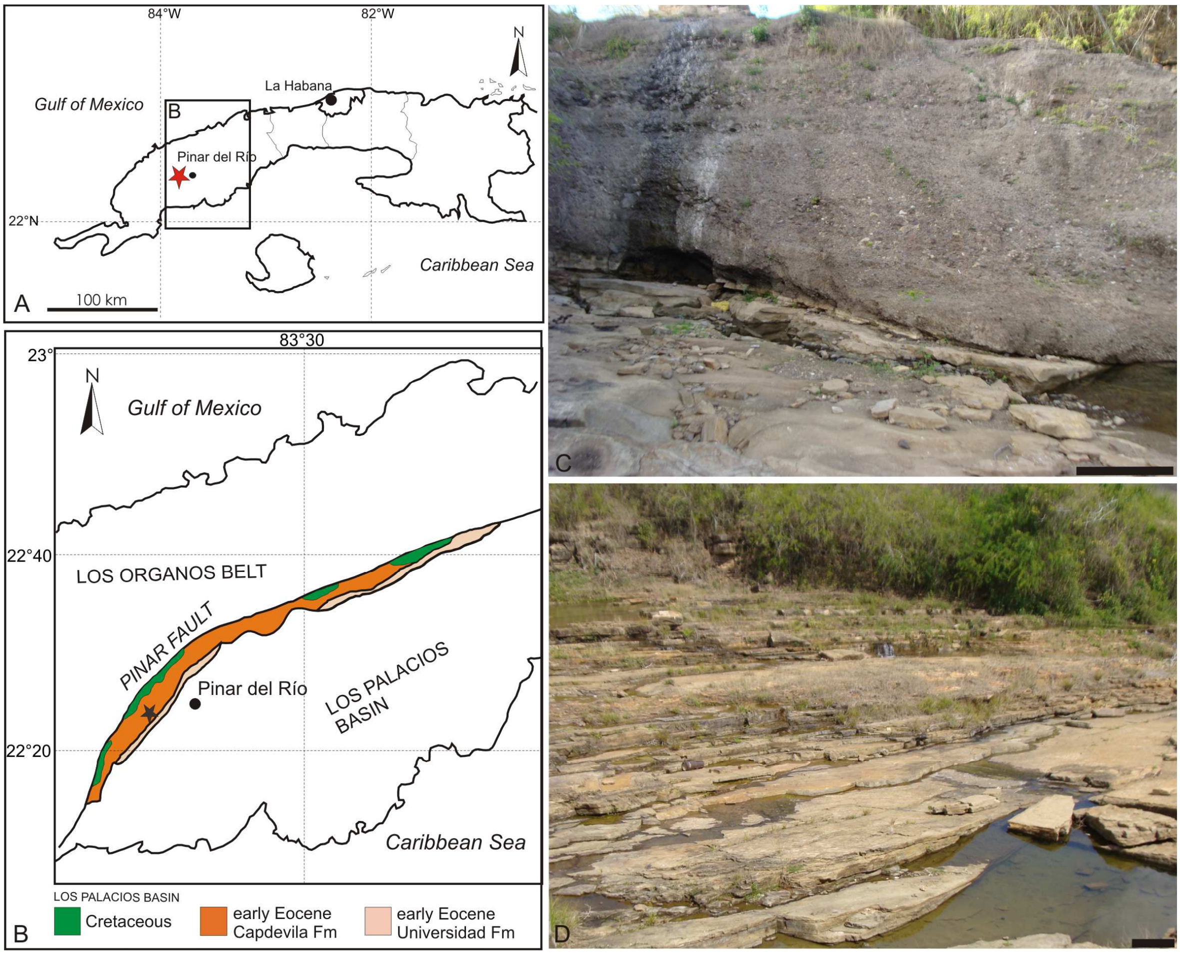

Figura 2. Mapa de localização geográfica (A) e geológica (B) da seção estudada pertencente à Formação Capdevila (ponto marcado por estrela), próximo da falha Pinar, que delimita a Bacia Los Palacios da Sierra de Los Órganos. (B) Modificado de Albear & Iturralde-Vinent (1985). (C, D) Visão da parte inferior (C) e superior (D) do afloramento.

4.2 Material

O estudo icnotaxonômico foi realizado a partir de observações diretas dos exemplares no afloramento e a partir do material proveniente da Formação Capdevila depositado na coleção paleontológica do Museo Nacional de Historia Natural de Cuba (MNHNCu-96.003567, MNHNCu-96.001291, MNHNCu-96.002933, MNHNCu-96.001297, MNHNCu-96.001292, MNHNCu-

96.001294, MNHNCu-96.003695, MNHNCu-96.001293, MNHNCu-96.001296, MNHNCu-96003689), incluindo o material que havia sido previamente trabalhado por Villegas-Martín & Rojas-Consuegra (2010).

4.3 Metodologia

Para a descrição e classificação dos icnofósseis foram usadas as icnotaxobases de Bromley (1996) que eran possíveis de observar no material estudado e foi feita a comparação com a literatura especializada. Estas bases incluem morfologia geral, orientação em relação ao substrato, tipo de parede, presença de ramificação (falsa ou verdadeira), preenchimento passivo (produto de um processo gravitacional) ou ativo (produto da própria atividadedo produtor), presença ou não de estruturas de *spreiten* e a posição em relação à estratificação (toponomia). Para a classificação dos traços fósseis em relação a aspectos toponômicos, neste trabalho foi utilizada a proposta de Seilacher (1964). As fotografias dos icnofósseis foram realizadas com luz natural, nos exemplares do afloramento e na coleção. Para a descrição da sucessão estudada, foram feitas duas saídas de campo onde foram descritas a litologia básica, as estruturas sedimentares primárias, o contato entre as camadas e as icnofábricas presentes. A elaboração do perfil e das figuras foi feita utilizando o programa Corel Draw versão 13.

A explicação mais detalhada dos materiais e métodos é dada em cada um dos artigos apresentados no item resultados e discussão.

5. RESULTADOS E DISCUSSÕES

Os resultados obtidos neste trabalho foram compilados na forma de três artigos científicos. Os artigos foram formatados de acordo com as normas dos periódicos escolhidos e o artigo 3 já foi submetido. Abaixo está o titulo de cada artigo, com uma breve descrição do conteúdo e a importância de cada um frente aos objetivos propostos.

5.1. Artigo 1

Preservational variations of *Scolicia:* morphological analysis of Paleogene echinoderm burrows from Cuba and ichnotaxonomical comments.

Este artigo apresenta uma análise morfológica de algumas estruturas pertencentes à Formação Capdevila encontradas em afloramento e na coleção. Os icnofósseis são atribuídos ao icnogênero *Scolicia* por apresentar principalmente bordos laminados e duas faixas ou cordões de sedimentos na região basal. As estruturas preservadas em epirrelevo negativo são identificadas como *Scolicia prisca* e as conservadas em epirrelevo positivo como *Scolicia var laminites.* A partir dos dados obtidos e sua comparação com dados da literatura, são feitas também algumas recomendações em relação a problemas icnotaxonômicos existentes para estas formas.

Este estudo revisivo foi necessário porque este material apresentava variações em muitos caracteres, e um estudo morfológico detalhado era necessário para esclarecer sua classificação icnotaxonômica, importante para a posterior realização das inferências paleoecológicas e paleoambientais. Neste sentido, destaca-se a existência no material estudado de formas semelhantes ao icnogênero *Psammichnnites* que constitui um traço fóssil de ambientes marinhos, principalmente rasos, ao contrário de *Scolicia,* que pode ser encontrada em uma ampla variedade de ambientes marinhos, desde rasos até profundos. Também foi necessário analisar o tratamento icnotaxonômico que havia sido dado às morfologias aqui identificadas como *Scolicia var laminites,* pois alguns autores seguem associando estas formas a táxons que já foram colocados em sinonímia e, portanto, não são mais utilizados. Assim, era necessária uma classificação icnotaxonômica adequada.

5.2. Artigo 2

***Bichordites monastiriensis* from the early Eocene of western Cuba**

Este artigo apresenta uma análise de morfologias encontradas em afloramento que são associadas ao icnogênero *Bichordites.* Foi realizada uma revisão do icnogênero e, a partir da comparação dos dados obtidos com os dados da literatura, o material foi atribuído com confiabilidade á icnoespécie *Bichordites monastiriensis*, por presentar principalmente um preenchimento laminado e um cordão central.

Este estudo foi necessário porque *Bichordites* é um traço principalmente reportado em ambientes marinhos de águas rasas. Um estudo morfológico detalhado era necessário para asegura a clasificação icnotaxonômica deste icnofóssil para que este resultado auxilie nas posteriores inferências paleoecológicas e paleoambientais.

5.3. Artigo 3

Ichnofabrics of the Capdevila Formation (early Eocene) in the Los Palacios basin (western cuba): paleoenvironmental and paleoecological implications

Este artigo apresenta o estudo da icnofauna do afloramento da Formação Capdevila, Bacia Los Palacios, em Pinar del Río. São identificadas e descritas nove icnofábricas, organizadas em quatro suítes. A partir dos resultados obtidos e a comparação com a bibliografia existente, foi possível fazer algumas inferências sobre as condições ecológicas prevalecentes sobre a comunidade bentônica, como a existência de um ambiente caracterizado por uma boa oxigenação, o predomínio de organismos detritívoros e um estresse ambiental por alta frequencia de aporte de sedimentos.

Este artigo constitui a etapa final do trabalho, onde se integram todos os dados icnológicos e sedimentológicos buscando responder aos objetivos da dissertação.

5.1. Artigo 1

Título

Preservational variations of *Scolicia*: morphological analysis of Paleogene echinoderm burrows from Cuba and ichnotaxonomical comments.

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Preservational variations of *Scolicia*: morphological analysis of paleogene echinoderm burrows from Cuba and ichnotaxonomical comments

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ABSTRACT

The ichnogenus *Scolicia* is the result of spatangoid echinoderms and they include bilobate and trilobate traces, laminated infills and the presence of two sediment strings, which can exhibit/show a great variety of shapes. Varied morphologies preserved in negative epirelief and positive hiporelief in sandstones of the Capdevila Formation (early Eocene) are assigned to *Scolicia*, the absence or presence of the sediment strings and of the laminated infill are some of the variations found in the preserved structures in negative epirelief and assigned to *Scolicia prisca.* The preserved structures in positive epirelief present a different grade of expression of the laminate and are assigned to the *Scolicia var laminites* variable.

Keywords: trace fossils, *Scolicia*, preservational variations, Capdevila Formation, early Eocene, Cuba.

1. Introduction

Scolicia was originally described by de Quatrefagues (1849), being assumed as fossil annelids. Its reinterpretation as trace fossil is a bit obscure and seems to be occurred in the first half of the 20th Century. The oldest putative record of *Scolicia* as a trace fossil was made by Seilacher (1955) who assumed it as a product of the gastropods activity (also Häntzchel 1975). Holoturians and crustaceans also had been proposed as *Scolicia* tracemakers (Ghent & Henderson 1966; Chamberlain 1971). However, natural observations and experiments in aquaria demonstrated that *Scolicia* is the burrow resultant of the grazing activity of spantagoid echinoderms with double drainage tubes (e.g. Ward &Lewis 1975; Bromley & Asgaard 1975; Smith & Crimes 1983; Bromley *et al*. 1997).

This ichnogenus had previously included a variety of morphologies that represented several ichnogenera such as *Psammichnnites, Subphyllocorda* and *Paleobullia,* among others (e.g. Häntzchel 1975; Ksiazkiewicz 1970, 1977; Smith & Crimes 1983; Plaziat & Plahmoudi 1988; Uchman 1995). Many of these morphologies had been excluded from or considered a synonym of *Scolicia*. Nevertheless, the complex morphological features that characterize this ichnogenus may be recorded as distinct preservational variations. The variability in the *Scolicia* preservation is mainly taphonomic and results of factors such as the burrow position within the sediment bed, erosion and litological diversity (Plaziat & Mahmoudi 1988; Uchman 1995; Gibert & Goldring 2008). However, only a few papers had directly focused this issue, analyzing the *Scolicia* morphological variations (Plaziat & Plahmoudi 1988, Smith & Crimes 1983, Bromley & Asgaard 1975).

Scolicia had been previously recorded in early Eocene deposits from the Capdevila Formation (western Cuba) (Villegas-Martín 2009), but detailed studies of these specimens as well as new ones revealed the occurrence of distinct preservational variations of *Scolicia* in the Capdevila Formation turbiditic beds. Thus, this paper aims to characterize the morphology of two preservational variations of *Scolicia* (*Scolicia prisca* and *Scolicia* var *laminites*) based on the specimens from the early Eocene of Cuba and discuss some of the existing problems in the *Scolicia* ichnotaxonomy.

2. Materials and methods

The specimens analyzed in this study occur in sandstone beds of the Capdevila Formation that crop out in the western Cuba. Part of the analyzed material is composed of specimens observed and described in the field and part is housed in the paleontological collection of the National Museum of Natural History (MNHNCu) in La Habana, Cuba (samples MNHNCu-96.003567, MNHNCu-96.001291, MNHNCu-96.002933, MNHNCu-96.001297, MNHNCu-96.001292, MNHNCu-96.001294, MNHNCu-96.001296, MNHNCu-96003689, MNHNCu-96.001295). The specimens assigned to *Scolicia* by Villegas-Martín (2009) are revised herein. The different morphologies were grouped based on their toponomy, using the classification proposed by Seilacher (1964).

3. Geographic and geological context

The studied samples come from two outcrops of the Capdevila Formation (Figure 1). Outcrop P 1 is placed in the northern part of the national highway La Habana-Pinar del Río, circa 4.5 km N to the Guanajay village, Province of Artemisa and outcrop P 2 is placed circa 20 km of the Pinar del Río city, Province of Pinar del Río. The samples housed in the MNHNCu collection come from the Pt 1.

The Capdevila Formation is well exposed in La Habana, Artemisa and Pinar del Río provinces, in western Cuba, forming part of the infill of the Anticlinal Havana–Matanzas and of the Los Palacios and Bahía Honda basins (Broniman & Rigassi 1963; Albear & Iturralde-Vinent 1985; Bralower & Iturralde-Vinent 1997; Gordon *et al.* 1997; García-Delgado & Torres-Silva 1997). This unit is mainly composed of carbonates in the lower part of the sedimentary succession, being the upper part dominantly siliciclastic, with predominance of massive and parallel-laminated sandstones forming tabular beds with normal or inverse gradation. Siltstones and conglomerates occur locally, which can be either supported by matrix or by grains (Bröniman & Rigassi 1963; Piotrowski 1987; Brust *et al.* 2011). Tuffites and carbonatic concretions had also been reported in some localities (Piotrowski 1987; Brust *et al.* 2011).

The foraminifer associations and the nanofossil zonation (NP 11 and NP 12 ODP zones, Site 865) place the Capdevila Formation deposits in the early Eocene (Bröniman & Rigassi 1963; Brönnimann & Stradner 1960; Bralower & Iturralde-Vinent 1997). Microfossils, corals (*Amphiroa*, *Lithophyllum*), echinoderm fragments, bivalves, brachiopods, and small fragments of macroscopic plants and red algae compose the paleontological record of the Capdevila Formation (Cushman & Bermudez 1949; Bronnimann & Rigassi 1963, Brönnimann & Stradner 1960; Piotrowski 1987; Bralower & Iturralde-Vinent 1997; Brust *et al.* 2011). According to Flügel (2004) and Brust (2006), several elements of this biota are typical of high-energetic shallow marine associations and characterize reworked material (Brust *et al.* 2011).

Preliminary ichnological studies carried out by Villegas-Martín (2009) in rocks of the Capdevila Formation from Artemisa revealed the existence of a more diverse ichnofauna, composed of the ichnogenera *Planolites, Ophiomorpha, Cosmorhaphe, Helmintorhaphe, ?Psammichnites* and *Scolicia*. Detailed studies on the ichnofauna from Pinar del Río area have been made recently by Villegas-Martín (2014) and revealed the dominance of *Scolicia, Thalassinoides, Bichordites, Palaeophycus* and *Ophiomorpha* in the trace fossil assemblage. Dense bioturbation of undetermined morphology, *Rhizocorallium* and rhizobioturbation occurs locally.

The deposition of the Capdevila Formation in the Pinar del Río area (Los Palacios Basin) apparently took place in a shallow slope developed in a strike-slip and piggy back basin presenting an half-graben geometry (Iturralde-Vinent 1995; Sommer 2009; Brust *et al*. 2011), which was placed at the south of the Pinar fault (western Cuba).

4. The ichnogenus *Scolicia* de Quatrefagues 1849

The name *Scolicia* was created by de Quatrefagues (1849) to identify a full relief structure found in Cretaceous deposits from the San Sebastian Bay, N Spain, that he considered the body fossil of an annelid. Later, a new specimen described by Savi and Meneghini (1851) was interpreted as the body fossil of an annelid preserved together with its trace fossil. Although the authors had been compared this specimen with *Scolicia* de Quatrefagues (1849), it was named *Nemertilites sardoa* due to the similarity with giant annelids of the living genus *Nemertes*. Almost a hundred years later, Seilacher (1955) described a complex trace fossil that combined the morphological characteristics of *Scolicia* and of several other ichnogenera (*Nemertilites, Fraena, Psammichnnites, Bolonia, Tetraichnites, Curvolithus, Subphyllocorda* and *Paleobullia*). This morphology was compared with that described as *N. sardoa* by Savi and Meneghini (1850) and assigned by Seilacher (1955) to *Scolicia* cf. *sardoa*, respecting the principle of priority in taxonomy.

Książkiewicz (1970, 1977) named as *Scolicia* the preservational variation like *Paleobullia* (recorded by Götzinger & Becker 1932) present in the Polish Carpathian deposits. Like de Quatrefagues (1849), Książkiewicz (1970, 1977) included in *Scolicia* only the groove (negative epirelief) preservational variation. However, a variety of ichnogenera, including *Suphyllocorda, Psammichnites, Bolonia, Scolithia, Palaeobullia, Olivellites, Paleobulla* and *Nemertilite* had been grouped by Häntzschel (1962, 1975) in the so-called "Scolicia Group". According to Häntzschel (1962, 1975) two main type-morphologies can characterize *Scolicia*, those included by Książkiewicz (1970, 1977) and also the full relief structures that belong to the so-called "*Subphyllochorda* Group*"* of Götzinger & Becker (1932). A diagnosis for the ichnogenus *Scolicia* was formulated by Smith & Crimes (1983) which included only the morphologies preserved in negative epirelief with laminated infill and showing the two basal parallel strings that characterize the drainage tubes (*S. prisca* preservational variation), excluding the morphologies related to the ichnogenus *Subphyllochorda.* These authors also recommend to restrict the use of the name *Scolicia* for the Mesozoic and Cenozoic specimens and to exclude the preservational variations commonly preserved in Paleozoic beds (*Psammichnites, Bolonia, Curvolithus, Aulichnites, Laminites*) from the "*Scolicia* Group". Plaziat & Mahmoudi (1988) illustrated the distinct morphologies of the preservational variations of *Scolicia* in *flysch*-type deposits, adopting a diagnosis similar to that proposed by Smith & Crimes (1983), but also including the occurrence of full relief structures, in minor scale, and the interpretation of *Scolicia* as a grazing burrow.

The last revision in *Scolicia* diagnosis was made by Uchman (1995) in which many of the ichnogenera mentioned as preservational variations of *Scolicia* (*Taphrhelminthopsis, Subphyllochorda* and *Laminites*) were included. According to Uchman (1995), these preservational variations are conditioned by the erosion and the position of the burrow in the sediment bed. Uchman (1995) also emended the *Scolicia* diagnosis, including the morphologies in negative epirelief, full relief and hiporelief, with a laminated infill and the presence of two parallel strings along their lower side.

5. Morphological description

5.1 Structures preserved in negative epirelief

The specimens preserved in negative epirelief came from samples MNHNCu-96.003567, MNHNCu-96.001291, MNHNCu-96.002933, MNHNCu-96.001297, MNHNCu-96.001292, MNHNCu-96.001294 and from direct observations in the outcrops.

The structures are horizontal to the bedding plane, preserved in fine to medium-grained sandstones and show straight to lightly meandering trajectory, with predominance of the latter. In longitudinal section, they occur as bilobate and trilobate grooves at the top of the beds (Figures 2, 3). The burrows are formed by two convex lateral walls and a floor (Figure 2). The burrow diameter varies all along the structure and the upper margins of the lateral walls are found overlying the bedding surface. Convex asymmetric ribs lightly inclined in relation to the longitudinal axis of the structure compose the burrow fill, being more marked in some portions. In most of the specimens, the floor is represented by a convex ridge and two parallel strings at each side, although there are portions of some specimens where the floor is characterized by a groove of different depths (Figure 2). The convex ridge has variable diameter and height and is covered by the asymmetric ribs. In cross section the burrows have low vertical depth in the sediment, show a semicircular bottom and a bilobate top composed by two parallel ridges. The length of the specimens varies from 157.9 to 198.7 mm and the width of the grooves varies from 29.2 to 31.6 mm. The ribs present a variable size, with length between 9.5 and 16.4 mm and width between 1.8 to 3.5 mm. The groove that characterizes the burrow floor is 2.0 to 3.8 mm wide.

5.2. Structures preserved in positive epirelief

The specimens preserved in positive epirelief came from samples MNHNCu-96003689, MNHNCu-96.001295 and from direct observations in the outcrops.

The structures are horizontal to the bedding plane in carbonates and fine to medium-grained sandstones, with a straight to inclined or lightly meandering trajectory. They are preserved as bilobate structures in longitudinal section at the top of the beds overlying the bedding surface (Figure 4). The burrow infill is formed by ribs of different sizes, being generally small and united (Figure 4). Some specimens are preserved at the bed surface and, in this case, the ribs are hardly seen or not seen at all. The ribs can be crossed in their central part by a shallow groove, being less evident in the specimens preserved in carbonates. In cross section they are bilobate and sediment strings can be observed in the lower portion of the burrow. The ribs are 25.5 to 32.7 mm long and 12.3 to 34.8 mm wide.

6. Assignation to *Scolicia* (de Quatrefagues 1849)

The studied material can be assigned to the ichnogenus *Scolicia* (de Quatrefagues 1849) due to the bilobate and trilobate morphology, the presence of a backfill infill and the potential presence of two parallel strings at the sides of burrow floor (Smith and Crimes 1983; Plaziat and Mahmoudi 1988; Uchman 1995).

6.1. *Scolicia prisca* de Quatrefagues (1849)

The morphologies preserved in negative epirelief can be trustfully assigned to *Scolicia prisca* de Quatrefagues (1849) (Figure 2), as they present a trilobate structure, with backfill infill, a floor formed by a laminated convex dorsal string and two parallel strings at both sides of the floor, in the lower portion of the burrow (Smith & Crimes 1983; Plaziat & Mahmoudi 1988; Uchman 1995).

Scolicia prisca corresponds to burrows made in the sand/mud interface, in which only the lower portion, excavated in the sand, is preserved (Plaziat & Mahmoudi 1988, Uchman 1995). Similar morphologies are produced at the substrate surface by modern spatangoid echinoderms in shallow marine settings (Figure 5). However, their potential of preservation is low due to the continuous action of erosive processes.

Some particular features concerning the presence of laminated walls, the preservation of the parallel strings and the dorsal convex ridge could be observed in the studied specimens and are discussed herein.

6.1.1. Laminated walls

The laminated walls are less evident in the specimens preserved medium-grained sandstones (Figure 2A) and are partially preserved in one specimen, in which only the dorsal ridge and the two parallel strings are visible (Figure 2). This particular preservation is a consequence of the erosion of the upper part of the full structure, as the part of the burrow that shows all the diagnostic characteristics occurs in deeper layers into the substrate. Plaziat & Mahmoudi (1988) illustrated specimens with similar morphology and assigned it to *Scolicia*, assuming it as an isolated preservation of the dorsal ridge.

6.1.2 Parallel strings and convex dorsal ridge

In spite of be preserved in the studied specimens, the parallel strings are not present in most of them, being replaced by two sediment rows (Figure 2). These sediment rows are well reported in *Scolicia prisca* (Ksiazkiewicz 1977; Bromley & Asgaard 1975; Smith & Crimes 1983; Plaziat & Mahmoudi 1988) and constitute the proof that the parallel strings had existed. The preservation of the parallel strings is either rare or occasional (Plaziat & Mahmoudi 1988; Smith & Crimes 1983) because they are empty tunnels that eventually collapse due to the sediment pressure (Kanazawa 1995) or due to the animal displacement (Smith & Crimes 1983). Backfill lamination may be preserved in the external surface of the parallel strings (Smith & Crimes 1983), but this feature has not been seen in the studied samples.

In some specimens the sediment rows can be tapered in some sections due to superimposition of the lateral walls over the dorsal ridge. This characteristic has already been mentioned for *S. prisca* by Donovan *et al.* (2005) and similar occurrences had been discussed by Plaziat & Mahmoudi (1988). According to Uchman (1995, 1998), a similar situation can be originated when the burrow occupies a deep position in the sandy portion of the beds the lateral walls rest over the dorsal ridge. The width of the dorsal ridge and the height of the lateral walls can vary along the same specimens in the studied material and can be equivalent in some specimens (Figura 2). Similar features were also observed by Uchman (1995) in *Scolicia* specimens.

6.2 *Scolicia* cf. *prisca*

The morphologies assigned to this category are preserved in negative epirelief and present a superficial groove in the floor (Figure 3). This groove is longitudinally disposed along the axis of the structure. In some specimens, remnants of the convex dorsal ridge can be preserved into the superficial groove, suggesting being this groove the original space occupied by the dorsal ridge and sediment rows. The presence of the dorsal ridge and the sediment rows remnants in the superficial groove, even locally, led to assume these specimens as *Scolicia* cf. *prisca* (sensu Uchman, 1995).

6.3. *Scolicia* var *laminites* Uchman 1995

The morphologies included in this classification are those described in positive epirelief (Figure 4) which can present parallel strings in the basal portion of the burrow, a bilobate top and with a laminated backfill (sensu Uchman, 1995). The laminated backfill is better visualized in the specimens preserved in carbonates. This preservational variation was proposed by Uchman (1995) to represent the preservation of the upper part of burrows that show similar morphologies, like *Psammichnites, Bichordites* and *Scolicia*.

The names *Scolicia* var *laminites* or *Scolicia* isp. have been used by Poiré *et al.* (2003) and Rebata *et al*. (2006) to characterize burrows showing the convex bilobate morphology that commonly characterizes the upper part of the structures included in *Scolicia* (the former "*Laminites"*), without making any reference to the presence of the parallel strings. Although the attribution to a non-specific ichnospecies is a common practice in ichnology, especially when clear diagnostic features are present, this must be avoided in the case of *Scolicia*, which only must be assumed if the identification of the parallel strings would be possible. If not, the well-stated attribution of *Scolicia* to the grazing activity of spatangoid echinoderms would be miscarried.

7. Conclusions

The bilobate and trilobite trace fossils preserved in negative and positive epirelief in the sedimentary rocks of the Capdevila Formation (western Cuba) can be assigned to the ichnogenus

Scolicia, representing the *S. prisca*, *S.* cf. *prisca* and *S.* var *laminites* preservational variations. The morphologies preserved in negative epirelief (grooves) are undoubtedly assigned to the *Scolicia prisca* and the observed variations in the diagnostic features (dorsal ridge, laminate backfill and parallel strings) reflect the wide variation that can be expected in the burrows made by spatangoid echinoderms.

The presence of the two parallel strings in the base of the flat, bilobate morphologies preserved in positive epirelief allow to assume these burrows as produced by spatangoid echinoderms represented by the *Scolicia* var *laminites* preservational variation.

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10. Figure captions

Figure 1. Sites from where the studied material came from. Highway La Habana-Pinar del Río (Pto 1) and surrondings of the Pinar del Río city (Pto 2), western Cuba.

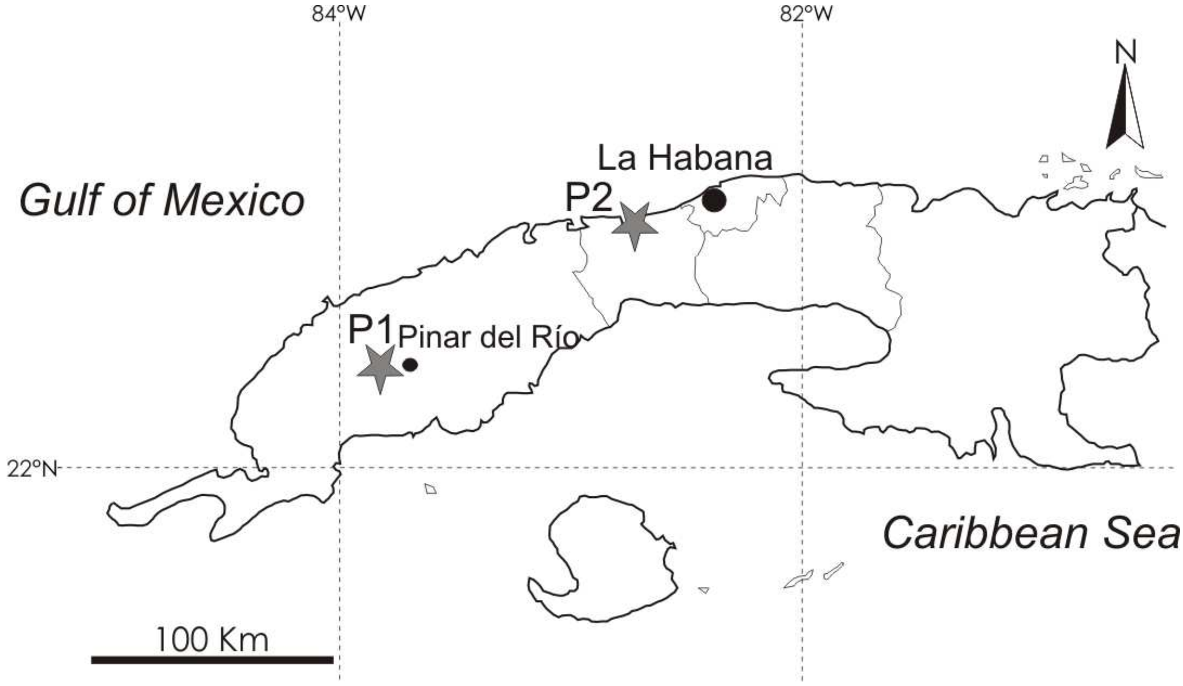
Figure 2. Main diagnostic features of *Scolicia prisca* and its variations in the studied specimens. A. Narrow dorsal ridge tapering at an end, sediment rows at each side of the burro floor, discrete laminated backfill. B, E. Specimen with well-preserved laminated backfill and parallel strings. C. Burrow lacking the laminated backfill and the dorsal ridge but showing discrete sediment rows. D. Burrow lacking the lateral walls and laminated backfill but showing the parallel strings. F.

Specimen showing faint lateral walls, wide dorsal ridge and narrow or absent sediment rows. Scale bars = 10 mm.

Figure 3. *Scolicia* cf. *prisca*. A, D. Specimen showing laminated walls and a visible median superficial groove. B. Dorsal ridge (black arrow). C. Cross section view showing the concave bottom and the bilobate top of the burrow. Scale bars = 10 mm.

Figure 4. *Scolicia* var *laminites.* A-B. Specimens with well-preserved laminated backfill. C-D. Bilobate top with discrete laminated backfill. C. Specimen with basal portion similar to *S. prisca.* E-F. Burrow cross-section showing the preserved parallel strings (black arrow). Scale bars = 10 mm.

Figure 5. A. Furrows made by the modern spatangoid *Spatangus purpureos* in the coast of Greece (depth = 3 m) (photo by Roberto Pillon) resembling *Scolicia prisca* (black square). B. *Scolicia prisca* from Capdevila Formation (early Eocene). Scale bars = 20 mm.


84°W
82°W
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La Habana
Gulf of Mexico
P2
P1
Pinar del Río
22°N
Caribbean Sea
100 Km

Figure 1

Figure 2

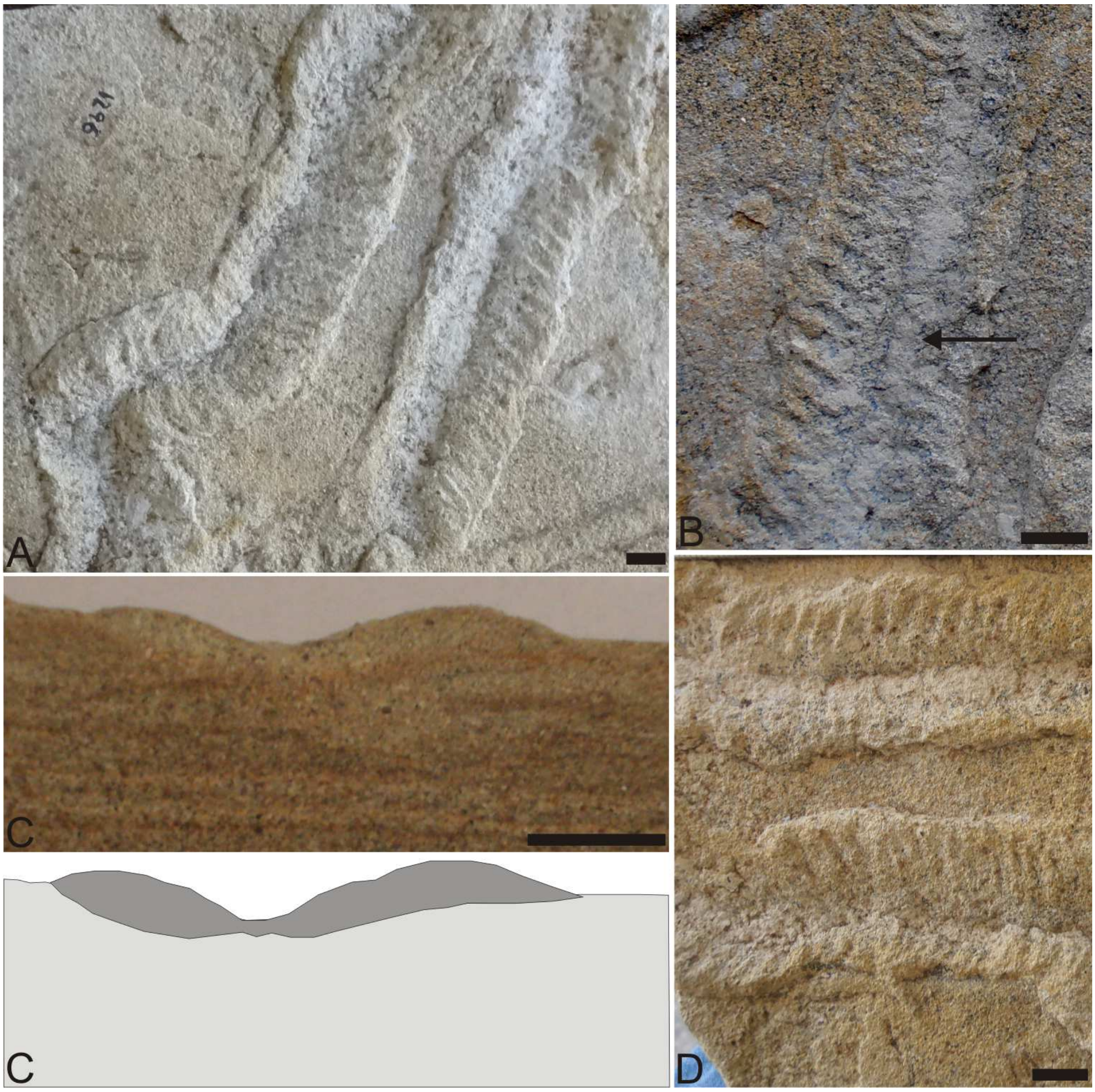

Figure 3

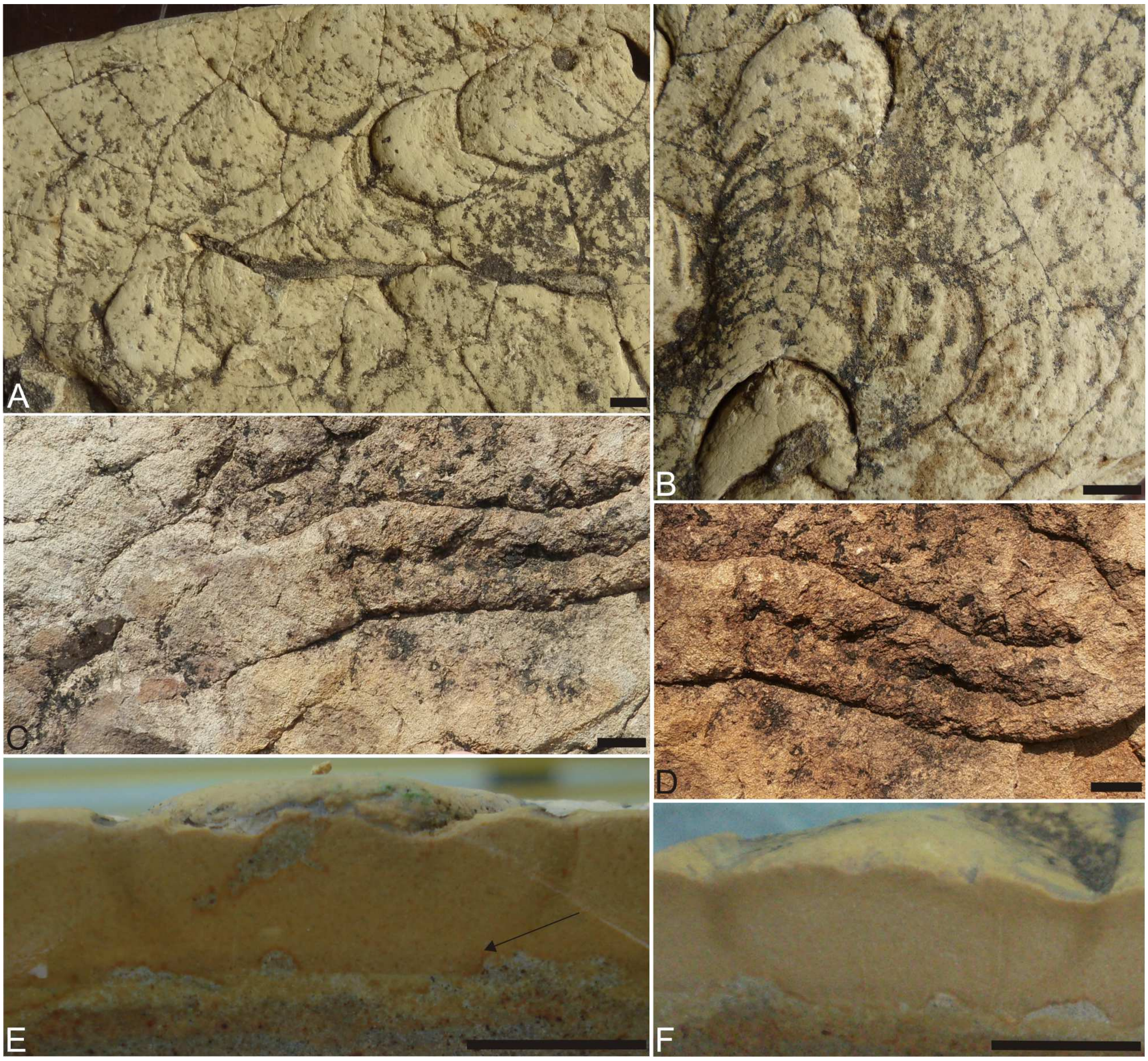

Figure 4

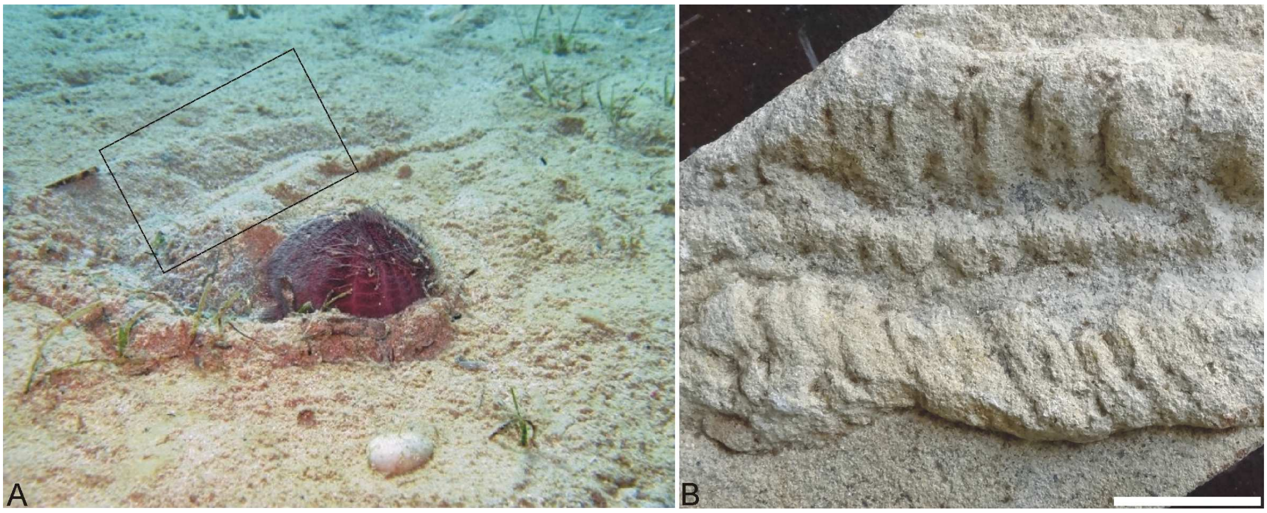

Figure 5

5.2. Artigo 2

Título

Bichordites monastiriensis from the early Eocene of western Cuba

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Periódico

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Bichordites monastiriensis from the early Eocene of western Cuba

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Abstract

This paper describes the oldest specimens of *Bichordites monastiriensis* which are preserved in early Eocene turbiditic sandstone beds of the Capdevila Formation in Los Palacios Basin, Pinar del Río region, western Cuba. An extensive review of the morphological characteristics of the *B. monastiriensis* revealed that the preservation of a single drainage core at the base of the central tube may be expected. Considering this feature, the diagnosis of the ichnogenus *Bichordites* was emended. The potential tracemakers of *B. monastiriensis* were analysed taking in account the spatangoid echinoderm fossil fauna present in Cuba and in the Caribbean seas, being the burrows attributed to the grazing activity of individuals from the Maretiidae Family.

Keywords: trace fossil, *Bichordites*, Capdevila Formation, early Eocene, western Cuba.

1. Introduction

Spatangoids compose an abundant group of irregular echinoderms that are successfully adapted to an infaunal-type life (Smith & Crimes 1983; Kanazawa 1992). The bioturbation produced by them is well known nowadays both due to natural observations and to experiments made in aquaria (Nichols 1959; Howard *et al.* 1974; Bromley *et al.* 1997) and plays an important role in the ecology of the marine benthic communities. For this reason, spatangoids are considered key-burrowers in marine ecosystems (Bromley *et al.* 1997).

In the fossil record, the ichnogenera *Scolicia* (Quatrefages 1849), *Bichordites* (Plaziat & Mahmoudi 1988) and *Cardioichnus* (Smith & Crimes 1983) are attributed to spatangoid grazing (the former two) and resting (the last one) activity into the substrate. The ichnogenus *Bichordites*, which is analyzed herein, is produced by spatangoids with a simple drainage tube (Plaziat & Mahmoudi 1988) and has been registered in marine Cenozoic deposits, from the Oligocene to the Pleistocene (Plaziat & Mahmoudi 1988; Pickerril *et al.* 1993; Uchman 1995; Uchman & Krenmayr 1995, 2004; Nara 2004; D'Alessandro & Fürsich 2005; D'Alessandro & Uchman 2007; Uchman & Pervesler 2007; Gibert & Goldring 2007, 2008; Aguirre *et al.* 2010; Bernardi *et al.* 2010; Demircan & Uchman 2012).

This work aims to record the occurrence of *Bichordites monastiriensis* in early Eocene deposits from western Cuba and to discuss its affinities with spantagoid echinoderms of the Family Maretiidae.

2. Materials and methods

The studied samples come from sandy deposits of the Capdevila Formation preserved in the Los Palacios Basin that crop out in the Pinar del Rio region, circa 20 km of the homonymous city (22°23'16.8" N, 83°47'10.4" W, Fig. 1). All the descriptive morphological data were obtained by direct observation in the field and followed the ichnotaxobases approach (Bromley 1996).

3. Geographic and geological context

The Capdevila Formation was originally described by Palmer (1934). Its deposits are well developed in the provinces of La Habana, Artemisa and Pinar del Rio in western Cuba (Bröniman & Rigassi 1963; Albear & Iturralde 1985), forming part of the infill of the Anticlinal Havana-Matanzas and of the Los Palacios and Bahía Honda basins (Albear & Iturralde-Vinent 1985; Bralower & Iturralde 1997; Bröniman & Rigassi 1963; García-Delgado & Torres-Silva 1997; Gordon *et al.* 1997). The unit is attributed to the early Eocene due to foraminiferal faunas (Bröniman & Rigassi 1963; Brönnimann & Stradner 1960) and nanofossil biozones (NP 11 and NP 12 biozones of ODP Site 865, according to Bralower & Iturralde-Vinent 1997). Bröniman & Rigassi (1963) made a detailed description of the Capdevila Formation, recognizing four mixed siliciclastic-carbonate units in the city of La Habana. In the Los Palacios Basin, the Capdevila Formation is formed by muddy, limestones and sandy sediments intercalated with carbonates, polymictic sandstones, and conglomerates (Piotrowski 1987; Brust *et al.* 2011).

The fauna reported for this unit is formed by a variety of microfossils that include foraminifera, ostracods and nanofossils, corals, echinoderm fragments, bivalves, brachiopods, and small fragments of macroscopic plants (Cushman & Bermudez 1949; Brönnimann & Rigassi 1963; Brönnimann & Stradner 1960; Piotrowski 1987; Brust *et al.* 2011). Bronnimann & Rigassi (1963) mentioned the occurrence of *Chondrites* in the deposits of the Capdevila Formation, but did not describe or illustrate the samples. Preliminary ichnological studies made by Villegas-Martín (2009) in rocks of the Capdevila Formation from Artemisa revealed the existence of a more diverse ichnofauna, composed of the ichnogenera *Planolites, Ophiomorpha, Cosmorhaphe, Helmintorhaphe, ?Psammichnites* and *Scolicia*. Detailed studies on the ichnofauna of this unit in the Los Palacios Basin had been made recently by Villegas-Martín (2014) revealed the dominance of *Scolicia, Thalassinoides, Bichordites, Palaeophycus* and *Ophiomorpha* in the trace fossil assemblage.

The deposits of the Capdevila Formation have been assumed as a bathyal marine sequence formed during an active tectogenesis period in which massive amounts of terrigenous materials were carried into the basin by turbiditic currents, forming a typical flysh-type deposition (Albear &

Iturralde-Vinent 1985). Recently, new studies carried out by Brust *et al.* (2011) placed the deposits of the Capdevila Formation in Pinar del Rio region in a slope, and the integrated analysis of the ichnology and sedimentology of these deposits led Villegas-Martín (2014) to infer deposition in a shallow slope.

4. The ichnogenus *Bichordites*

Plaziat & Mahmoudi (1988) erected the ichnogenus *Bichordites* based on the description of materials from Tunisia which were assumed as pseudoburrows due to the diameter variation all along each burrow, among other characteristics. The authors did not propose a diagnosis for the ichnogenus, just for the type-ichnospecies, *Bichordites monastiriensis*, in which the central core was described as representing the whole burrow. Full relief morphologies showing the outer zone that surrounds the central core were illustrated by Plaziat & Mahmoudi (1988, p. 217, figs. 8-9), who assumed them as an association linking the *Bichordites* and *Laminites* ichnogenera.

A diagnosis for the ichnogenus *Bichordites* was proposed later by Pickerill *et al.* (1993) based on the detailed description made by Plaziat & Mahmoudi (1988) and additional material from Jamaica, but still only referring to the central core. The authors also stated that the apparent infill present in *Bichordites* could represent a bigger burrow backfill, being the central core (= *Bichordites* at that moment) a component of a more complete echinoderm burrow system.

Uchman (1995), in a revision of the ichnotaxa attributed to spatangoid echinoderms, emended the existent diagnosis for *Bichordites* including the central core as an integral part of a burrow with a backfilled infill. This diagnosis was also assumed for *Bichordites monastirienses*, emphasizing that only the central core is usually preserved.

Demircan & Uchman (2012) emended the *Bichordites* diagnosis proposed by Uchman (1995) restricting it to a dominantly horizontal meniscate complex burrows with a bilobated central core. Burrows are non-branched, cylindrical or subcylindrical in cross section, and show straight to meandering trajectory. The authors also erected a new ichnospecies, *Bichordites kuzunensis*, and proposed that the new diagnosis included both morphologies, because the previous one was only applicable to *Bichordites monastiriensis*.

The diagnosis proposed by Dermican & Uchman (2012) for the ichnogenus *Bichordites* is slightly modified herein to include the preservation of the true drainage tube within the central core. This preservation was documented by Demircan & Uchman (2012) in *Bichordites kuzunensis* specimens and by Bernardi *et al.* (2010) in *Bichordites monastiriensis*, constituting a common characteristic in both ichnospecies. The average diameter of the drainage tube in *B. monastiriensis* is 1mm and between 1-1.5 mm in *B. kuzunensis*.

5. Ichnotaxonomy

Bichordites (Plaziat & Mahmoudi, 1988)

Type-ichnospecies*:* *Bichordites monastiriensis* (Plaziat & Mahmoudi, 1988)
Emended diagnosis*:* Complex non-branched meniscate burrow, mainly horizontal, cylindrical or subcylindrical in cross section, with straight or meandering trajectory, in which a small bilobate central core can be preserved. The true drainage tube can be preserved in the basal portion of the central core (modified from Demircan & Uchman 2012).

Bichordites monastiriensis (Plaziat & Mahmoudi, 1988)

(Fig. 2)

Diagnosis*:* Predominantly horizontal, cylindrical, straight to winding, unbranched, meniscate composite burrow, slightly concave along the base and the tope, and with central cord. At least the upper part of the burrow contains a double row of menisci. The cord is preferentially preserved; it is heart-shape to ovoid in cross-section, tapers locally and is interrupted. A longitudinal median shallow groove along the top of the cord locally passes into an indistinct crest. Locally, the cord is covered with external irregular constrictions or transverse striae (after Uchman 1995).

Description*:* Subhorizontal to horizontal cylindrical burrows preserved in full relief at the top of medium-grained sandstone beds, with a straight to strongly curved trajectory describing an almost 90° angle when turning. The burrows are smooth-walled, non-branched, and crossed by a heart-shaped central core (Fig. 2C). A meniscate infill can be present surrounding the central core (Fig. 2B). The diameter of the preserved central core is variable, being bigger in one extreme of the burrow than in the other. The central core infill is similar to that of the whole burrow and corresponds, in a general sense, to the matrix of the host rock, in spite of being darker in the undersized extreme. In cross section, a discrete subcircular groove infilled by sediment is observed in the upper part of the central core (Fig. 2), which is overlaid by a subcircular ridge. The biggest diameter of the burrow is approximately of 4 cm and the smallest 3 cm. The distance between the central core and the limit of the burrow is approximately 2 cm.

Discussion*:* The lacking of a keel-like morphology in the lower portion of the burrow and the absence of a mantle differentiate *Bichordites monastiriensis* from *Bichordites kuzunensis* described by Demircan & Uchman (2012). Nevertheless, the presence of a keel-like structure in the lower portion of *B. monastiriensis* was documented by Pickerill *et al.* (1993) and included by these authors as a possible morphological variation in the *B. monastiriensis* diagnosis. The presence of a heart-shaped central core in the studied specimens allows to include it in *B. monastiriensis* (Plaziat & Mahmoudi 1988; Pickerill *et al.* 1993; Nara 2004).

The preservation of the central core embedded by the menisci laminated infill led to infer that the burrows described herein represent the full structure generated by the tracemaker (spatangoid echinoderms). Similar specimens were described by Bernardi *et al.* (2010), but showing a drainage tube in the median basal portion of the central core, a feature that was not observed in the studied specimens. According to Bromley & Asgaard (1975), the drainage tube is barely reported in *Bichordites monastiriensis* specimens, which disappears when the echinoderm moves upwards or downwards in the burrow. The common preservation shows only the central core as it constitutes a well-cemented zone by sediment mucus-enrichment that envelopes the drainage tube (Bromley & Asgaard 1975). The heart-shape of the central core could be caused by the collapse of the drainage tube and posterior cementation, while the ovoid shape could represent rapid active sediment infill of the drainage tube during the animal displacement and quick cementation (Bromley & Asgaard 1975).

Bichordites monastiriensis have been recorded mainly in shallow marine deposits from the Oligocene to the Pleistocene, having a broad geographical distribution including Tunisia (Plaziat & Mahmoudi 1988), Jamaica (Pickerril *et al.* 1993) Japan (Nara 2004), Italy (Uchman 1995; Bernardi *et al.* 2010) and Austria (Uchman & Krenmayr 1995).

6. The tracemaker

Spantangoids characterize a group of echinoderms well-known since the Early Cretaceous (Kier 1977; Villier *et al.* 2004), although trace fossils (*Scolicia*) attributed to these organisms were reported in earlier ages (Tchoumatchenco & Uchman 2001). Two distinct ichnogenera are attributed to spatangoid grazing activity, *Scolicia* and *Bichordites,* which were assumed as produced by echinoderms with two and one drainage tubes, respectively (Uchman 1995). *Bichordites* is attributed to echinoderms of the *Echinocardium* group due to presence of specimens of *Echinocardium cordatum* (Echinocardiidae) in these burrows preserved in life position, as described by Bromley & Asgaard (1975). These authors also suggested that other species of *Echinocardium* excavate burrows with a simple drainage tube and stated that the presence of a single drainage tube is an exclusive characteristic of Echinocardiidae (Asgaard & Bromley 2007). However, Gibert & Goldring (2007, 2008) attributed the Miocene *Bichordites* specimens found in Alicante Province, SE Spain, as produced by echinoderms of the genus *Maretia* (Maretiidae), based in the occurrence of complete spatangoid body fossils associated with the burrows. The record of body fossils of *Eupatagus ornatos* (Maretiidae) in life position inside of *Bichordites monastiriensis* in Oligocene deposits from Italy (Bernardi *et al.* 2010) reinforces the hypothesis that maretiids can also produce *Bichordites*.

The record of the Echinocardiidae Family is unknown either in Cuba or in the Caribbean seas (Mihaljević *et al.* 2010). Pickerill *et al.* (1993) also did not assume *Echinocardium* as the tracemakers of the *Bichordites* specimens found in the Pleistocene deposits from Jamaica because no record of these organisms were known in this island since the Cenozoic. Nevertheless, the Maretiidae Family is known in the Caribbean seas, being recorded in Barbados, Jamaica, Cuba and Antigua, among other islands (Jackson 1922; Sánchez Roig 1949; Donovan & Lewis 1993; Donovan 1993; Donovan *et al.* 2005). In particular, the genera *Eupatagus* and *Maretia*, which were also assumed as *Bichordites* tracemaker by Gibert & Goldring (2007, 2008) and Bernardi *et al.* (2010), are registered as body fossils in Cuba (Donovan & Lewis 1993; Sánchez Roig 1926) and Jamaica (Jackson 1922).

Thus, although no body fossil of echinoderms had been found in the studied outcrop, maretiid echinoderms, particularly individuals of the genera *Eupatagus* and *Maretia* are assumed as potential tracemakers of the *Bichordites monastiriensis* specimens found in the early Eocene deposits of the Capdevila Formation in Los Palacios Basin. This statement led to infer that maretiids might also be the tracemaker of the *B. monastiriensis* specimens studied by Pickerill *et al.* (1993) in the Old Pera Formation (Jamaica).

7. Conclusions

The presence of the *Bichordites monastiriensis* in the sandstone beds of the Capdevila Formation in western Cuba places the oldest record of *Bichordites* in the early Eocene. The possible conservation of the true drainage tube within the central core in *B. monastiriensis* allows refining the ichnogenus diagnosis, which is now emended. Individuals of the Maretiidae Family are suggested as a potential *Bichordites* tracemaker in the Caribbean seas, and in particular in the island of Cuba.

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9. References

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10. Figure captions

Figure 1. Geographic location (A) and geological (B) maps of the Pinar del Río area (western Cuba) where the sedimentary succession of the Capdevila Formation crops out (star)**.**

Figure 2. A**.** *Bichordites monasteriensis*. B. Detail of the meniscate backfill that surrounds the central core. C. Detail of the heart-shape of the central core.

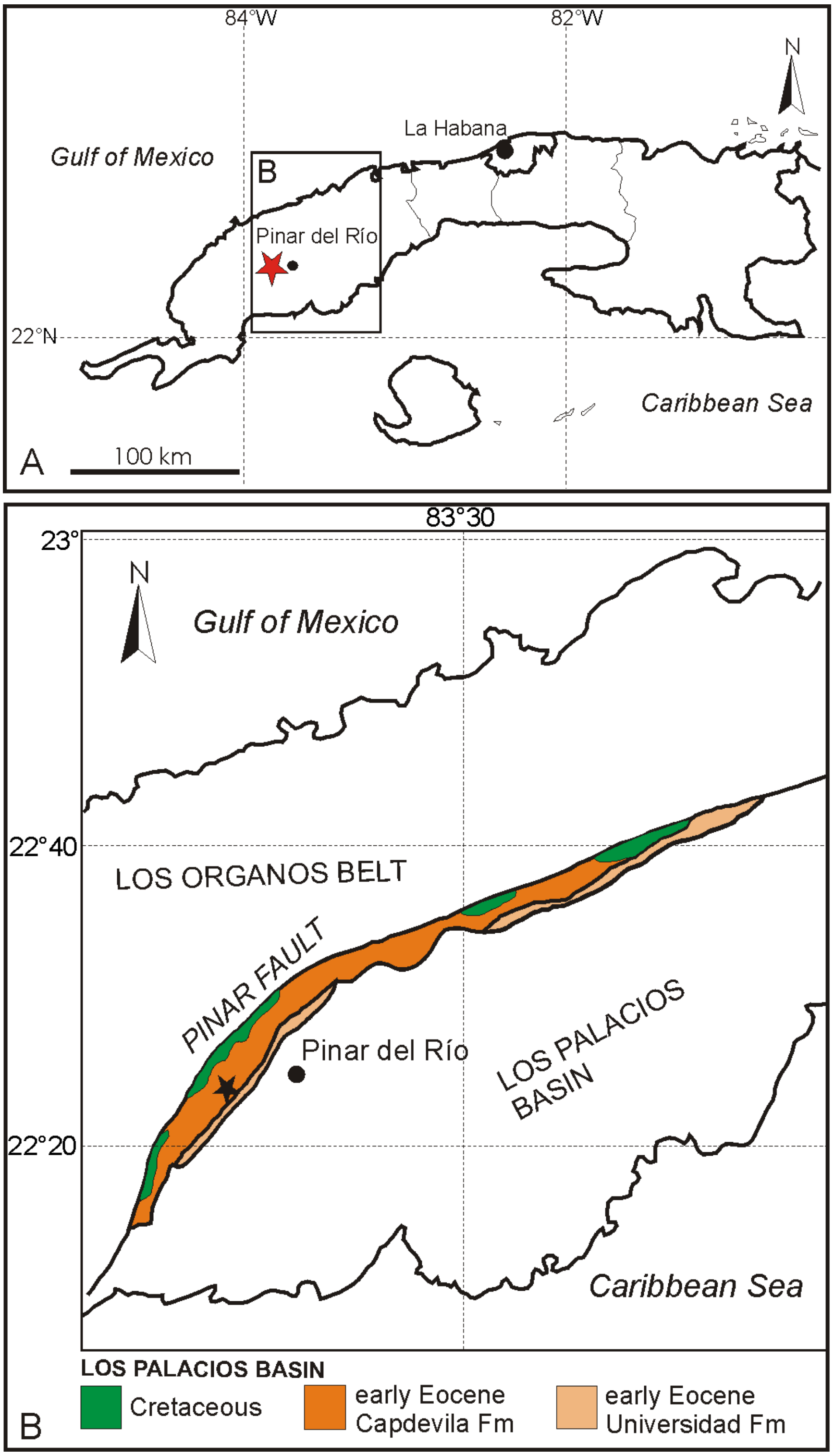
84°W
82°W
N
La Habana
Gulf of Mexico
B
Pinar del Río
22°N
Caribbean Sea
A
100 km
83°30
23°
N
Gulf of Mexico
22°40
LOS ORGANOS BELT
PINAR FAULT
Pinar del Río
LOS PALACIOS BASIN
22°20
Caribbean Sea
LOS PALACIOS BASIN
Cretaceous
early Eocene Capdevila Fm
early Eocene Universidad Fm
B

Figure 1

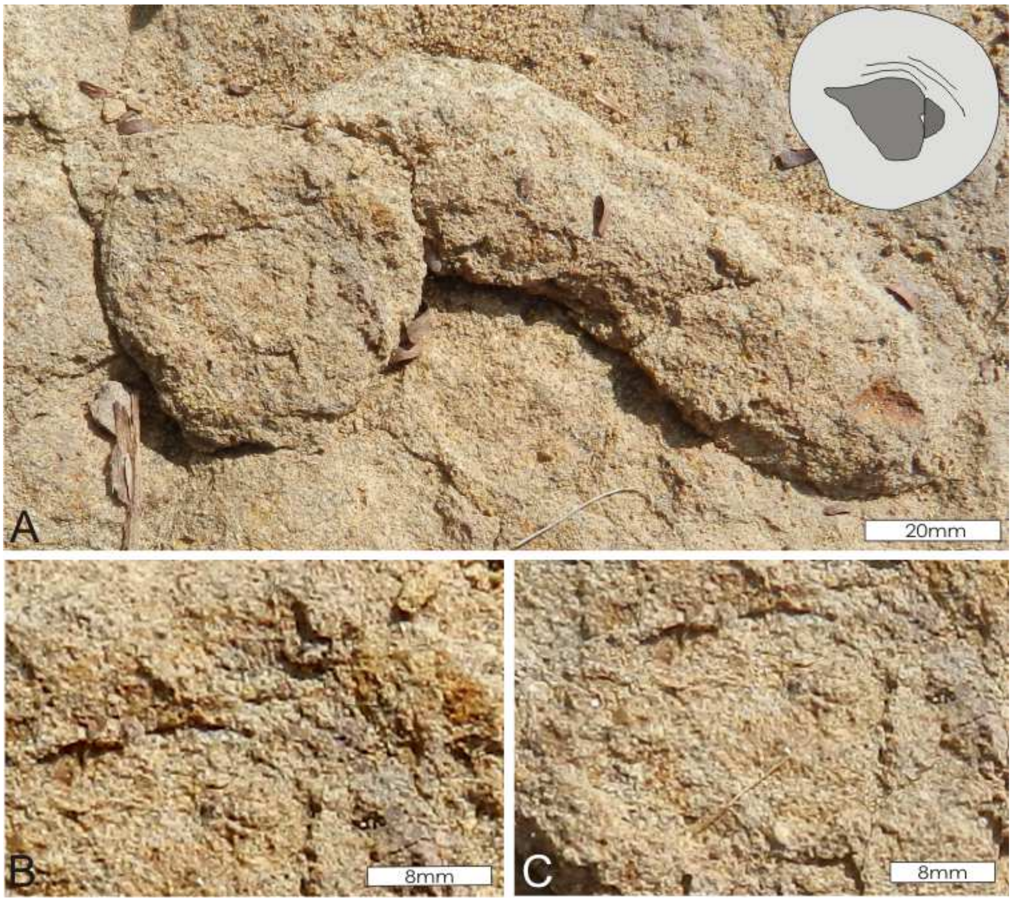

Figure 2

5.3. Artigo 3

Título

Ichnofabrics of the Capdevila Formation (early Eocene) in the Los Palacios basin (western Cuba): paleoenvironmental and paleoecological implications

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ICHNOFABRICS OF THE CAPDEVILA FORMATION (EARLY EOCENE) IN THE LOS PALACIOS BASIN (WESTERN CUBA): PALEOENVIRONMENTAL AND PALEOECOLOGICAL IMPLICATIONS

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ABSTRACT

The ichnofabrics present in the early Eocene siliciclastic deposits of the Capdevila Formation exposed in the Pinar del Rio area (Los Palacios Basin, western Cuba) are analyzed in this paper and its paleoecological and paleoenvironmental significance are discussed. Nine ichnofabrics could be recognized in the dominantly sandy sedimentary succession: *Ophiomorpha, Asterosoma, Thalassinoides, Palaeophycus, Scolicia, Bichordites-Thalassinoides, Rhizocorallium, Scolicia-Thalassinoides* and rhizobioturbation. The ichnofauna is low diverse and burrows made by detritus-feeding organisms in well oxygenated and stenohaline waters predominates. Suites of the Cruziana and Skolithos ichnofacies lacking their archetypical characteristics were recognized, being impoverished in diversity and presenting dominance of echinoderm and decapods crustacean burrows as a response to the environmental stress caused by the high frequency of deposition. The ichnofabric distribution in the studied succession, its recurrence in the sandstone beds and the presence of a Glossifungites Ichnofacies suite with rhizobioturbation associated reflect a shoaling-upward event with subaerial exposure of the substrate. The integrated analysis of the ichnology and the sedimentary facies suggests deposition in a shallow slope frequently impacted by gravitational flows and high-energy events. The evidence of substrate exposure indicates the occurrence of a forced regression and suggests the existence of a sequence boundary at the top of the Capdevila Formation.

Keywords: ichnology, turbidites, Eocene, Capdevila Formation, Cuba.

1. INTRODUCTION

Trace fossils are known due to their importance to help evaluating different aspects such as substrate consistency, salinity, oxygenation, and hydrodynamic energy for paleoecologic and paleoenvironmental reconstructions (e.g. Buatois and Lopez-Agriman, 1992; Buatois and Mángano, 2011; Buatois et al., 2010; Netto and Rossetti, 2003; Netto et al., 2009; Uchman, 1991, 1992). In Cuba, the use of the ichnofossils for these interpretations are scarce, being only mentioned in literature under mistaken or obsolete terms such as: “biogliphes”, “hieroglyphic”, “traces”, “channels”, “bioturbation”, or “bioerosion” (Albear and Iturralde-Vinent, 1985; Jakus, 1983; Pszczółkowski, 1987; Rojas-Consuegra, 1999). Only in some recent studies these structures are being identified and have received more attention (Menedez et al., 2011; Pszczółkowski, 2002; Pszczółkowski and Myczynski, 2009; Villegas-Martín and Rojas Consuegra, 2011; Villegas-Martín et al., 2012).

In the Capdevila Formation the ichnological record is restricted to *Chondrites* in outcrops in the La Habana region (Brönnimann and Rigassi, 1963) and the occurrence of abundant trace fossils in the Los Palacios Basin (Brust et al., 2011). Nevertheless, materials present in the paleontological collection of the National Museum of Natural History of Cuba revealed the existence of a particular ichnofauna in Eocene deposits of the Capdevilla Formation, which is subject of study in this work.

Thus, the objectives of this contribution are three-fold: (i) to identify and to describe the ichnofossils of the studied section, (ii) to recognize the facies associations and the trace fossil assemblages present in the succession and (iii) to analyze in an integrated way the facies and the ichnofauna of the Capdevila Formation to support paleoenvironmental and paleoecological interpretations.

2. MATERIALS AND METHODS

The ichnofossils were described through direct observations in the field and specimens from the paleontological collection of the National Museum of Natural History of Cuba (samples MNHNCu-96.003567, MNHNCu-96.001291, MNHNCu-96.002933, MNHNCu-96.001297, MNHNCu-96.001292, MNHNCu-96.001294, MNHNCu-96.001296, MNHNCu-96003689, MNHNCu-96.001295). The descriptions and ichnotaxonomic classification were done following the main ichnotaxobases proposed by Bromley (1996) and the stratinomic classification of Seilacher (1964). The bioturbation index (BI) was measured based on the scale proposed by Reineck (1967). The sedimentary facies are described taking into account lithology, physical sedimentary structures, bed contacts and ichnofabrics.

3. GEOGRAPHIC AND GEOLOGICAL CONTEXT

3.1 Los Palacios Basin

The Los Palacios Basin is strike-slip and piggy-back basin (Iturralde-Vinnent, 1995, 1996; Brust et al., 2011; Sommer, 2009) presenting an half-graben geometry placed at the south of the Pinar fault in western Cuba (Figure 1), which formed syn-to post-orogenic (Maastrichtian–Eocene) sediment traps derived from emerged land sections (Burst et al., 2011). Its deposits are mainly Paleogene and Neogene in age, although it goes from the Upper Cretaceous (Maastrichtian) to the Quaternary (Bralower and Iturralde, 1997).

According to stratigraphic studies (Piotrowski, 1987; Bralower and Iturralde, 1997), the basin infill starts with a predominance of fossiliferous (rudists) limestones, sandstones and conglomerates (in minor scale) deposited in a shallow marine environment, barely affected by tectonic activity (Martinez and San Juan formations). The Vibora Group (late Paleocene) unconformably overlays the basal deposits and also consists of limestones, fine-grained sandstones and conglomerates. The Capdevila Formation comprises the overlying succession that is separated from the Vibora Group by a depositional hiatus. It is characterized by coarse-grained siliciclastic sandstones, conglomerates and calcareous sandstones deposited under predominant marine conditions during the basal early Eocene.

During the Eocene the basin was strongly affected by tectonic activity that caused its uplift upward and local emergence of some portions. The deposition generated at this time characterizes the sedimentary succession of the Capdevila Formation. The basin stabilization after these events originated the deposition of hemipelagic marly chalks that characterizes the Universidad Formation (upper early Eocene) (Piotrowski, 1987). A depositional hiatus occurs between the latter and the Loma Candela Formation (medium Eocene) which is characterized by the sedimentation of conglomerates, limestones, sandy carbonates and sandstones (Piotrowski, 1987). Two hypotheses were suggested for this tectonic activity during the Eocene, one attributed to orogenic movements in the Guaniguanico mountains at the end of the collision in western Cuba (Piotrowski, 1987) that took place between the late Paleocene and the early Eocene (Bralower and Irurralde-Vinnent, 1997) and another related to block movements all along the Pinar fault during the early Eocene (Gordon et al., 1997). It was suggested that the source areas of the sediments were sourad from an elevated area situated at the NE of the basin (Brust et al., 2011).

3.2. Capdevila Formation

The Capdevila Formation was originally described by Palmer (1934). It comprises an up to 400 m-thick, well-exposed succession in the provinces of La Habana, Artemisa and Pinar del Rio (western Cuba), forming part of the infill of the Anticlinal Havana–Matanzas and Los Palacios and Bahía Honda basins (Albear and Iturralde-Vinent, 1985; Bralower and Iturralde, 1997; Bröniman and Rigassi, 1963; García-Delgado and Torres-Silva, 1997; Gordon et al., 1997). The unit is attributed to the early Eocene due to foraminiferal faunas (Bröniman and Rigassi, 1963; Brönnimann and Stradner, 1960) and nanofossil biozones (NP 11 and NP 12 biozones of ODP Site 865, according to Bralower and Iturralde-Vinent, 1997).

Bröniman and Rigassi (1963) made a detailed description of the Capdevila Formation, recognizing four mixed siliciclastic-carbonate units in the city of La Habana. In the Los Palacios Basin the lower part of the Capdevila Formation is formed by muddy and sandy sediments intercalated with carbonates while sandstones, conglomerates and few mudstones predominate in the upper part (Brust et al., 2011). The fauna reported for this unit is formed by a variety of microfossils that include foraminifera, ostracods and nanofossils, corals (*Amphiroa*, *Lithophyllum*), red algae (*Solenopora*), echinoderm fragments, bivalves, brachiopods, and small fragments of macroscopic plants (Brönnimann and Rigassi, 1963; Brönnimann and Stradner, 1960; Brust et al., 2011; Cushman and Bermudez, 1949; Piotrowski, 1987).

The Capdevila Formation has been interpreted as a bathyal marine sequence formed during an active tectogenesis period in which massive amounts of terrigenous materials were carried into the basin by turbidity currents, forming a typical flysh-type deposition (Albear and Iturralde-Vinent, 1985). Recently, new studies carried out by Brust et al. (2011) in the deposits of the Capdevila Formation in Pinar del Rio region placed its accumulation in a slope associated with a narrow platform.

3.3. Geology of the study area

The studied section (Figure 2) corresponds to the upper part of the Capdevila Formation in the Los Palacios Basin (Figure 1). It is approximately 20 km northeast from the Pinar del Rio city (22°23'16.8" N and 83°47'10.4" W), in the province of Pinar del Rio, close to the Pinar fault (tectonic limit between the Guaniguanico mountains and the Los Palacios Basin) (Figures 1A-B). It is mainly formed by tabular sandstone beds of different grainsizes with predominance of massive and parallel-laminated beds (Figure 2).

Six sedimentary facies were recognized in the study area: (i) massive sandstones; (ii) fluidized sandstones; (iii) sandstones with parallel lamination; (iv) sandstones with ripples; (v) siltstones; (vi) paraconglomerates (Table 1, Figures 3, 4).

Table 1. Sedimentary facies observed in the studied section.

Facies	Description	Interpretation
Massive sandstones	Tabular sandstones of different granulometries (fine to very coarse) forming amalgamated beds up to 70 cm thick that sometimes show a normal gradation. Clasts of assorted grainsize (up to boulders) can be present in the base of the coarse-grained sandstones locally forming ortoconglomerates. Wood fragments are abundant in the beds of medium granulometry. It contains the ichnofabrics of *Ophiomorpha, Thalassinoides,*	Resultant deposits of gravity sediment flows. The beds of fine to medium-grained sandstones correspond to the F8 of Muttti (1992) while the coarse-grained sandstone beds correspond to the deposits F5 of Mutti (1992). They suggest the action of high-concentration turbidity flow (Walker, 1965).

	Bichordites-Thalassinoides and Scolicia-Thalassinoides.	
Fluidized sandstones	Tabular sandstones of different granulometries (fine to coarse), that form amalgamated beds up to 50 cm thick sometimes showing normal gradation. Beds are fluidized and wood fragments are abundant in medium-grained sandstones.	Resultant deposits of sediment gravity flows equivalent to the F5 and F8 of Mutti (1992). They result from high-concentrated turbidity flows and reflect a rapid deposition (Stow et al., 1996).
Sandstones with parallel lamination	Tabular sandstones of different granulometry (fine to coarse) with parallel lamination. Beds with normal grading forming thinning-upward cycles grading to sandstones with ripples are locally observed, as well as boulders of volcanic rocks in the base of some beds. Wood fragments can be found in the medium to fine-grained sandstones. It contains the ichnofabrics of *Thalassinoides*, *Palaeophycus*, *Scolicia*, *Bichordites-Thalassinoides*, *Rhizocorallium* and rhizobioturbation.	Resultant deposits of sediment gravity flows equivalent to the F9 of Mutti (1992). They result from turbidity flows of upper regime (Stow et al., 1996).
Sandstones with ripples	Tabular sandstones with fine to medium granulometry with unidirectional ripples mainly preserved at the top of the beds.	Resultant deposits of sediment gravity flows equivalent to the F9 of Mutti (1992). They result from low concentration turbidity currents under lower flow

		regime condition (Stow et al., 1996; Walker, 1965).
Siltstones	Massive siltstones homogenized by intense bioturbation. It contains the *Asterosoma* ichnofabric.	Resultant deposits of low intensity flows and decantation, to the F9 of Mutti (1985). Consequence of the sediment settlement carried mainly in suspension (Stow et al., 1996).
Paraconglomerates	Polimitic conglomerates supported by matrix, composed by fine to coarse gravels and forming lenticular beds. The matrix is composed of medium to very coarse-grained sandstones. Normal and inverse gradation can be observed in the beds. Angular, subrounded and rounded clasts are present, with a predominance of the first ones. Clasts can touch each other locally.	Resultant deposits of sediment gravity flows. They correspond to the F2 of Mutti (1992) and characterize cohesive-matrix detritic flows that represent channel infill. .

The sandy facies predominate and are genetically related, their tabular geometry suggest deposition in turbidity lobes. The sandstones with ripples settle over the sandstones with parallel lamination forming thinning-upward cycles. The massive sandstone facies can conforms the base of these cycles but, in general they appear isolated in the succession, suggesting frequent erosion. Muddy deposits are rare reinforcing the idea of highly erosive processes or high depositional frequency.

The base of the sucession in the study area is characterized by the recurrence of the sandstone facies with *Ophiomorpha* ichnofabric in the massive sandstones at the top of this succession (Figure 3). Fluidized sandstones rich in wood fragments (Figure 4G) overly the basal sandstones which are overlain by thick lenses of paraconglomerates, representative of high energy channeled. The presence of the siltstones facies with the *Asterosoma* ichnofabric over the paraconglomerates indicates the establishment of low hydrodynamic energy conditions. The high-energy processes were resumed with the entrance of the sandstone facies forming thinning-upward cycles which are rich in marine ichnofabrics. All this takes place in the middle part of the succession (Figure 3, Table 1). The ichnofabric pattern of these cycles suggests a shoaling upward that ends with the exposure of the substrate as attested by the occurrence of rhizobioturbation. The upper portion of the succession is characterized by the sandstone cycles with marine ichnofabrics which are frequently interrupted by deposition of massive sandstones, suggesting the return of the high depositional frequency conditions.

The deposits described in the study area are equivalent to those described by Brust et al. (2011) for the upper portion of the Capdevila Formation in the Los Palacios Basin. Brust et al. (2011) related the deposition of the paraconglomerates to tectonic activity along the Pinar Fault zone (Figure 1 D).

4. ICHNOFABRICS OF THE CAPDEVILA FORMATION

Nine ichnofabrics could be recognized in the Capdevila Formation in the study area. Except for *Bichordites monastiriensis, Scolicia prisca* and *Scolicia* var *laminites*, all the biogenic structures present in the ichnofabrics were identified down to the ichnogenus level as they do not present morphologies that allow the observation of ichnospecific features.

4.1. The *Asterosoma* ichnofabric

It is formed by *Asterosoma* (Figures 5A-B) and dense undetermined bioturbation, showing a BI 5, locally 6. The structures attributed to *Asterosoma* show a star-like shape, constituted by a central subcircular or circular tube, from which four elongated bulbous-like, sub-rounded ending tunnels with smooth edges emerge. *Asterosoma* is preserved in negative and positive epirelief at the top of the siltstone beds (Figure 3).

4.2. The *Thalassinoides* ichnofabric

Composed exclusively of *Thalassinoides* (Figures 5C), with BI 3-4, which occurs as a dychotomic-branched burrow system with horizontal and vertical components, predominating the horizontal ones and presenting a straight to lightly inclined trajectory. In many cases the burrows were observed as independent Y-shaped short fragments. The burrow walls are smooth and circular or subcircular in cross section. The infill is equal to the host rock. The burrows are preserved at the top of the beds of the sandstones with parallel lamination and medium grained massive sandstones facies (Figure 3).

4.3. The *Scolicia* ichnofabric

It is composed exclusively of *Scolicia* (Figure 6 C-F), presenting a BI 2-3 and preserved in positive and negative epirelief at the top of the sandstones with parallel lamination facies (Figure 3). The structures preserved in negative epirelief are assigned to *Scolicia prisca* (sensu Uchman 1995, Figures 6 C-F) and show a straight to lightly meandering trajectory in certain portions. They are preserved as grooves formed by a floor and two lateral walls. The upper margins of the lateral walls are lightly elevated just over the surface of the bed; the walls go from inclined to lightly curved and can be covered by asymmetric size-varied laminae. The floor is convex, being either smooth or presenting a laminated infill. Two sediment strings are disposed at each side of the floor, close to the lateral walls. In cross section they have subcircular or U-shaped form. Branches are not observed. The structures preserved in positive epirelief are assigned to *Scolicia* var *laminites* (sensu Uchman, 1995; Figure 6F). In longitudinal section it characterizes a bilobated burrow with a median groove. The burrow infill is formed by barely visible menisci. The burrows show a lightly meandering trajectory. In some samples, features of *S. prisca* morphology can also be distinguished. Small wood fragments were found in *Scolicia* ichnofabric-bearing beds.

4.4. The *Rhizocorallium* ichnofabric

It is only formed by *Rhizocorallium* (Figures 6A-B), with BI 1-2. It is characterized by U-shaped burrows disposed parallel or slightly inclined to the bedding plane which are subcilindrical in cross section. The characteristic *spreiten* is absent and scratch marks are common in the burrow wall. Branches are lacking. *Rhizocorallium* is preserved in positive epirelief, in the fine to medium-grained sandstones beds with parallel lamination (Figure 3). Abundant organic material was found at the level containing this ichnofabric.

4.5. The *Palaeophycus* ichnofabric

It is formed exclusively by *Palaeophycus* (Figures 7C, D) and shows a BI 2-3. Horizontal, non-branched burrows with a mainly inclined trajectory and infill of the same matrix as the host rock predominate in this ichnofabric. A discrete lining is observed in the burrow wall which is irregular in some portions. The burrows are preserved as positive epirelief in the fine to medium-grained sandstones beds with parallel lamination (Figure 3).

4.6. The *Bichordites-Thalassinoide*s ichnofabric

It is composed of *Bichordites, Thalasssinoides* and *Palaeophycus* with BI 3-4, being *Bichordites* and *Thalassinoides* the most common ichnogenera. *Bichordites* is represented by the ichnospecies *B. monastiriensis* (*sensu* Uchman, 1995) (Figures 7A, C, E). It is formed by non-branching, subhorizontal and horizontal burrows with an inclined to straight trajectory, circular to subcircular in cross section, crossed by a central string that can either have a circular or hearty form. A concentric lamination infill can be observed in some specimens (Figures 7A, C). A discrete groove can be present in the upper part of the central string and a ridge can appear over the central string, in some specimens. The samples of *Thalasssinoides* and *Palaeophycus* in this suite present the same morphological characteristics as the homonymous ichnofabrics described in 4.2 and 4.5. The burrows are preserved in semirelief and in epirelief in beds rich in wood fragments of the fine to medium-grained sandstones beds with parallel lamination, as well as of the medium-grained massive sandstones beds (Figure 3).

4.7. *Scolicia-Thalassinoides* ichnofabric

It is formed by *Scolicia*, *Thalasssinoides,* rare *Palaeophycus* (Figures 6, 7) and undetermined bioturbation with BI 3-4. The burrows are preferentially horizontal to the bedding plane. The best preserved samples of *Scolicia* can be attributed to *S. prisca* and are preserved in negative epirelief, with a lightly meandering to straight trajectory. The morphology is equivalent to that described in the *Scolicia* ichnofabric. The morphology of *Thalassinoides* and *Palaeophycus* is also equivalent to that previously described in the homonymous ichnofabrics. It is preserved in the fine-grained beds of the massive sandstone facies (Figure 3).

4.8. The *Ophiomorpha* ichnofabric

It is formed exclusively by *Ophiomorpha* (Figure 7F), presenting BI 2-3. The burrows are mainly vertical in relation to the bedding plane, circular in cross section, with a peletted lining. Pellets are irregularly distributed through the burrow wall and isolated pellets can occur locally. Branches are rarely observed. The burrow infill is the same of the host rock. The burrows are preserved in full relief in beds of the massive sandstones facies (Figure 3).

4.9. The rhizobioturbation ichnofabric

It is composed of branched, irregular, horizontal, tiny (1-2 mm in diameter) tubules infilled with organic-rich sediment, showing BI 1-2 (Figure 5 D, E). The tubules are characterized by an irregular longer central stem from which shorter secondary ramifications are originated. The tubules diameter is highly variable all along each tubule and terminations are acute or subrounded. The diameter variation in a same tubule, the acute terminations and the absence of a regular dychotomic-branching pattern allow to infer rhizobioturbation and to distinguish it from *Chondrites*. Similar structures were also described by Uchman and Bromley (2003) as rhizobioturbation. This ichnofabric occurs in fine to medium-grained beds of the sandstones with parallel lamination facies (Figure 3).

5. PALEOECOLOGICAL ANALYSIS

The ichnofauna of the Capdevila Formation is mostly composed of truly marine ichnotaxa which reflect well-oxygenated substrates. *Thalassinoides*, *Scolicia* and *Bichordites* are the most common ichnogenera and are good indicators of the oxic conditions (Bromley et al., 1995). The burrows preserved in the Capdevila Formation deposits reflect temporary or permanent domicile of polychaetes and decapod crustaceans, as well as epifaunal or infaunal displacement of irregular echinoids, and suggest the prevalence of detritivorous-feeding organisms in the endobenthic community (Bromley, 1996; Buatois and Mángano, 2011). The ichnodiversity, in general, is low and the amount of bioturbation is moderate, locally high.

Four paleoichnocoenoses could be differentiated in the studied section, according to the composition and distribution of the ichnofabrics and the nature and consistency of the substrate: (i) distal Cruziana, represented by a suite of soft substrates of low energy that suggests pre-event colonization (*sensu* Howard 1978); (ii) impoverished Cruziana, represented by a suite of soft substrates of moderate to high energy that suggest post-event colonization; (iii) Skolithos, represented by a suite of soft substrates of high energy that also suggests post-event colonization;

and (iv) Glossifungites, represented by a suite of firm substrates that suggests an omission suite (*sensu* Bromley, 1975).

The suite of soft substrates of low energy (SL) occurs exclusively in the siltstones facies (Table 1) and is composed of the *Asterosoma* ichnofabric. *Asterosoma* has been mainly reported in shelf environments, being more frequent in lower energy zones and in offshore settings (e.g. Bromley and Uchman, 2003; Vossler and Pemberton, 1989). Although less common, *Asterosoma* has also been reported in turbiditic-influenced zones (Powichrowski, 1989; Rindsberg, 1982). The high amount of bioturbation in SL suite and its occurrence in siltstones indicate the predominance of low energy and more stable conditions, which allowed the accumulation of organic detritus in the substrate and favored the intense activity of detritivorous organisms. In the substrate tiering, *Asterosoma* generally occupies the medium to deep tiers, being a common element in the historical layer. This layer is less affected by the superficial erosion (Bromley, 1996) and, for this reason, shows intense bioturbation. The dominance of *Asterosoma* in SL suite suggests that their producers were the last settlers of the substrate.

The suite of firm substrates (SF) is characterized by the *Rhizocorallium* and rhizobioturbation ichnofabrics. It presents low ichnodiversity and punctual occurrence of the bioturbation. The absence of spreiten and the presence of irregular walls with scratch marks in *Rhizocorallium* indicate excavation in stiffgrounds (Gingras et al., 2000) and shoaling-upward deposits. The occurrence of rizhobioturbation suggests the subaerial exposure of the substrates. The preferential horizontal distribution and the apparently simple structure of the rizhobioturbation (small diameter and little development of the rootlets) suggest a relatively short period of subaerial exposure and the establishment of pioneer vegetation, capable of rapidly colonizing a denuded sandy substrate. Saha et al. (2010) has reported a similar situation in coastal marine regions where *Rhizocorallium* occurs with rhizobioturbation.

The suite of soft substrates of moderate to high energy (SM) is characterized by the *Thalassinoides*, *Scolicia*, *Paleophycus, Scolicia-Thalassinoides* and *Bichordites-Thalassinoides* ichnofabrics. The exclusive presence of *Thalassinoides* ichnofabric in several beds of the studied succession suggests substrates affected by high energy events. These events might either inhibiting the colonization by other detritus-feeding organisms whose traces are common in outer shelf settings or destroying the burrows made in the upper tiers (e.g. Gibert and Martinell, 1998a). The *Thalassinoides* tracemakers (callianassid crustaceans) are capable of excavating in depths near to 2 m low in the sediment (e.g. Dworschak and Rodrigues, 1997) and survive to erosive events caused by the action of currents. Frequent moderate to high energy processes can generate sandy substrates in deeper areas, favoring the establishment of stable populations of deep-gallery burrowers in detriment of those made by shallower ones, as well as those made from organisms living in low energy settings. In this way, *r*-selected organisms such as some decapod crustaceans have more chance to survive to the stress established in these environments by the high energy or the high frequency of the processes (e.g. Pemberton et al., 2001). Nevertheless, the abundance of *Thalassinoides* in the studied deposits and its presence in the composition of several ichnofabrics that characterize the SM suite suggest the existence of optimal conditions for the *Thalassinoides* tracemakers, not representing here an opportunistic behavior.

Scolicia and *Palaeophycus* ichnofabrics occur in the fine to medium-grained sandstones with parallel lamination facies, being *Scolicia* the dominating one, while the *Scolicia-Thalassinoides* ichnofabric occurs in the fine-grained massive sandstones facies (Figure 3). The variation of the ichnodiversity and the amount of bioturbation among the ichnofabrics in SM suite are apparently related to the energy of the processes that conditioned the sandstones deposition. Therefore, the *Scolicia* and *Palaeophycus* ichnofabrics represent substrates affected by more frequent deposition, while the *Scolicia-Thalassinoides* ichnofabric represents substrates affected by less frequent deposition. Wood fragments can be found in the beds bearing the SM suite, being less frequent in those beds where the *Scolicia-Thalassinoides* occurs. That backs up the idea that those beds have been deposited under more energetic conditions or in areas which are closer to the vegetation source.

Trace fossil assemblages including *Thalassinoides*, *Palaeophycus* and *Scolicia* ichnogenera are reported in marine environments from shoreface to slope (e.g. Crimes et al., 1981; Buatois et al., 2003; Uchman, 1995), being the record of *Scolicia* abundant in deep marine deposits influenced by turbiditic currents since the Mesozoic (Wetzel and Uchman, 1998, 2001; Uchman, 1995, 1998). According to Uchman (1995), the *S. prisca* morphologies found in deep-marine turbiditic facies correspond to the basal portion of spatangoid burrows made in the mud-sand interface (post-event colonization), whose top was eroded by the turbiditic currents. The absence of the lateral walls or their small height in many specimens of *S. prisca* preserved in the study area demonstrates the dominance of erosion processes. *S. prisca* is mostly reported in turbiditic deposits of deep marine waters (Rodriguez-Tovar et al., 2010; Uchman, 1995; Wetzel and Uchman, 1998, 2001). Modern *Scolicia* tracemakers (*Spatangus* group, Smith and Crimes, 1983) live in benthic settings from shelf to deep slope, preferring sandy substrates (Kanazawa, 1992; Kroh and Hansson, 2013). The abundance of *Scolicia* in the soft substrate of moderate to high energy suite could be a response to the preference of their tracemakers for sandy substrates, being these more tolerant than the other organisms to the increase in the sedimentation rates (sensu Vermeij, 1978).

According to Aguirre et al. (2010), frequent sedimentation pulses with little or none erosion favor the establishment of echinoderm populations in the substrate. Having this in mind, the dominance of the *Scolicia* ichnofabric in some beds can reflects not only the action of high energy processes but also the existence of frequent deposition.

The *Bichordites-Thalassinoides* ichnofabric occurs in the sandstones with parallel lamination facies and the main components of this ichnofabric are commonly recorded in shelf environments, having *Bichordites* been recorded mainly in shallow water settings (Aguirre et al., 2010; Bernardi et al., 2010; Gibert and Goldring, 2008; Nara, 2004; Plaziat and Mahmoudi, 1988; Pickerril et al., 1993). *Bichordites* is the product of the displacement of spatangoid echinoderms, mainly *Echinocardium* and *Maretia* (Bromley and Asgaard, 1975; Gibert and Goldring, 2008). These organisms are distributed up to 150 m depth in modern seas (Kanazawa, 1992; Mortensen, 1951), being *Echinocardium* (*E. cordatum*) restricted to the first 40 m (Ernsts et al., 1973; Howard et al., 1974; Kanazawa, 1992). Under 30 to 40 m depth, the individuals of the genus *Echinocardium* lose their reproductive capacity (Buchanan, 1966), which restrict them to the shallowest settings. Their presence in lower depths (50 to 150 m) is related to storm events (Radwanski and Wysocka, 2001) that exhume the individuals of the shallow substrates and carry them to deeper areas. The abundance of wood fragments associated to the *Bichordites-Thalassinoides* ichnofabric might indicate proximity of the continental settings or an increase in the fluvial discharges.

The *Bichordites-Thalassinoides* and *Scolicia-Thalassinoides* ichnofabrics in the SM suite show a relatively bigger ichnodiversity if compared with the other ichnofabrics which suggest more stable conditions in the substrate, with a decrease of the deposition frequency.

The soft substrate of high energy suite (SH) is composed exclusively of the *Ophiomorpha* ichnofabric that occurs in the fine to medium-grained beds of the massive sandstones facies disposed in the lower portion of the sedimentary succession (Figure 3). The predominance of vertical burrows in subaqueous sandy substrates, in general, reflects high energy conditions, being mainly related to shallow settings where the action of waves or tides predominate (Buatois and Mangano, 2011). The substantial presence of *Ophiomorpha* in shoreface substrates since the Mesozoic reflects the efficiency of the callianassid decapods in creating extensive galleries in these settings (Frey et al., 1978), being assumed as beachline biomarkers (Pollard et al., 1993). However, the fining-upward arrangement of the beds containing the *Ophiomorpha* ichnofabric, the absence of sedimentary structures generated by wave or tide action, and the occurrence of paraconglomerates overlying these deposits suggest deposition in deeper settings, below storm wave base.

Ophiomorpha has also been reported in offshore deposits (Manley and Lewis, 1998) and in deep marine waters influenced by turbiditic currents (Uchman, 1995, 1998), in which it represents pioneer colonizing (*sensu* Föllmi and Grimm, 1990), characterizing opportunistic behavior (Crimes, 1977).

The paleoichnocoenoses of the Capdevila Formation and the recurrence of the trace fossil suites throughout the studied succession suggest that burrowing vagile organisms such as echinoderms, crustaceans and polychaetes were favored by the colonization windows generated in each event of significant sediment input in deeper zones, being these organisms able to (i) surviving to the erosion of the shallow substrates and tolerate the transportation by dense currents to deeper settings and (ii) settling in the new substrates after each event (e.g. Savrda et al. 1998).

6. PALEOENVIRONMENT INTERPRETATION

The recognized paleoichnocoenoses in the deposits of the Capdevila Formation are representative of the Cruziana, Skolithos and Glossifungites ichnofacies. Except for the Glossifungites Ichnofacies, the other two represent, in the studied deposits, impoverished expressions of their archetypal equivalents. The clear dominance of turbidites in the studied section (Table 1) suggests deposition in a slope context. The massive occurrence of trace fossil suites that are commonly present in shelf environments and the lacking of suites representative of the Nereites Ichnofacies suggest a shallow context in the slope realm (Wetzel and Uchman, 1998). This interpretation coincides with that stated by Brust et al. (2011) for the Capdevila Formation in the Los Palacios Basin. Similar trace fossil suites have also been recognized in sandy facies of upper slope deposits in different basins (e.g. Crimes, 1977; Crimes et al., 1981; Cummings and Hodgson, 2011; Shultz and Hubbard, 2005). Except for *Bichordites*, all the other ichnogenera present in the ichnofauna of the Capdevila Formation can be found in slope deposits (Hubbard et al., 2012).

The low ichnodiversity and the predominance of only one trophic strategy (detritus feeding) of mainly truly marine organisms in the studied deposits do not reflect the typical conditions of the Cruziana Ichnofacies (Buatois and Mángano, 2011). This situation together with the predominance of the monospecific ichnofabrics suggests environmental stress (Buatois and Lopez-Agriman, 1992; Uchman, 1992; Buatois et al., 2010). The establishment of the impoverished suites of Cruziana Ichnofacies is mainly attributed to the dominance of high frequency deposition. The abundance of wood fragments in several sandstone beds with SM suite indicates the input of continental debris due to fluvial discharges, which could produce salinity fluctuations in the slope area. This hypothesis is coherent with the existence of a narrow shelf affected by a fluvio-deltaic system during early Eocene in the Los Palacios Basin, which resulted in the deposition of the Capdevila Formation (Brust et al., 2011). However, the abundance of *Scolicia* and *Bichordites* in the studied section indicates that, if these discharges really existed, they were sporadic and not so intense as to inhibit the stenohaline fauna. The record of spatangoid bioturbation in stressed substrates of distal delta front and prodelta is scarce (Mcllroy, 2007) and can be related to the previous occupation of the substrate before the arrival of the continental input.

The post-event colonization is represented by the SM and SH suites, being the former recurrent all along the succession. This colonization is restricted to some beds, while others have no apparent bioturbation. Non-bioturbated intervals would represent deposits generated under higher energy conditions and by high depositional frequency that would inhibit colonization. The preferential preservation of the bioturbation at the top of the beds might suggest rapid colonization of the new ecospaces as the energy or the frequency of the sedimentation pulses decrease. Similar situations have been reported in literature and attributed to high sedimentation rates and frequent turbulence (Gibert and Martinell, 1998a, 1999). According to Mellere et al. (2002), the predominance of sandstones and the general scarcity of trace fossils indicate a high sedimentation rate. In environments subject to high sedimentation rates, a short period of deposition ceasing can be enough to allow biological activity (Buatois et al., 1997). The absence of ichnofabrics in the sandstone with ripples facies suggests that the bioturbated beds would be the relicts of deposits that were eroded by to the action of high energy flows.

The Cruziana Ichnofacies suites are mostly distributed in shelf deposits, from upper shoreface to lower offshore (Pemberton et al., 1992; MacEachern et al., 2007; Buatois and Mangano, 2011), so their presence in slope deposits could be assumed as atypical. However, suites of Cruziana Ichnofacies have been reported in slope deposits as a consequence of an well-oxygenated substrate (e.g. Buck and Bottjer, 1985; Savrda et al., 2001; Shultz and Hubbard, 2005; Wetzel, 2008). Thus, the occurrence of suites representative of the distal Cruziana Ichnofacies in the Capdevila Formation (the SL suite) is assumed as the result of the substrate colonization in the offshore-slope transition previous to the arrival of the gravitational flows (pre-event colonization).

The SF suite evidenciates the temporary exposure of the substrate in which it is preserved and characterizes the Glossifungites Ichnofacies (e.g. Pemberton and Frey, 1985). The presence of a suite representative of the Glossifungites Ichnofacies at the top of the beds containing the suites of the Cruziana Ichnofacies deposited in offshore-slope transition (SL suite) and in slope settings (SM suite) reveals the subaerial exposure of these substrates and suggests a significant base level fall, remarking the existence of a forced regression event in the basin during the early Eocene. The Glossifungites Ichnofacies has been reported in exhumed substrates of the submarine canyon edges in slope settings and in areas influenced for high-energy recurrent currents, being assumed as a sequence boundary biomarker (e.g. Savrda et al., 2001; Pemberton and MacEachern, 2005; Dasgupta and Buatois, 2012).

The SH suite represented by the *Ophiomorpha* ichnofabric represents an impoverished expression of the Skolithos Ichnofacies in the Capdevila Formation deposits. Its occurrence exclusively in the massive sandstones facies overlain by the paraconglomerate deposits in the lower portion of the sedimentary succession suggests opportunistic occupation of the sandy substrate accumulated in the slope by decapods transported from the shelf by turbidity currents. The amount of burrows in the *Ophiomorpha* ichnofabric diminishes as the sandstone grainsize decreases suggesting that capacity of exhumation of the active currents in shallower settings might be reduced. The occurrence of Skolithos Ichnofacies in deep marine turbiditic deposits is common, mainly in the surroundings of the submarine canyons and upper slope zones (Crimes, 1977; Crimes et al., 1981; Heard and Pickering, 2008).

Therefore, the ichnological analysis of the studied deposits reveals that the substrate occupation by the burrowing benthic fauna mainly took place in a shallow slope (Figure 8) after the depositional events and was conditioned by high energy flows or high depositional frequency. The presence of an impoverished Skolithos Ichnofacies suite in the massive sandstones of the lower portion of the succession, whose deposition was interrupted by the thick paraconglomerate deposits, indicates the action of more energetic processes in the slope area, possibly related to the presence of channels. The establishment of distal Cruziana Ichnofacies suites in a thin bed of the siltstone facies over the paraconglomerate deposits indicates the substrate occupation by a resident benthic fauna (pre-event colonization) and reflects the returning of the low energy, stable marine conditions which are normally characteristic of the offshore-slope transition area. That condition indicates a reduction of the impact of the progradational flows in the basin. The progradational flows are then reactivated, establishing the deposition of turbidite lobes, which dominate the upgoing succession. The impoverished Cruziana Ichnofacies turns to be the dominant ichnological context and a shoaling-upward tendency is observed up to the subaerial exposure of the substrate, marked by the replacement of the *Thalassinoides, Scolicia* and *Palaeophycus* ichnofabrics for that of *Bichordites-Thalassinoides* and then by the Glossifungites Ichnofacies suite. The latter indicates an omission suite and delimits a coplanar surface, formed by a forced regression surface and a later flooding surface. The anew dominance of the turbiditic sandy facies with the recurrence of the impoverished

Cruziana Ichnofacies suites indicates the returning of the progradational flows and the reestablishment of the high frequency deposition.

7. CONCLUSIONS

The integration of the ichnological and sedimentological analyses of the Capdevila Formation sedimentary succession in the Los Palacios Basin allowed to establish the deposition in shallow slope settings impacted by frequent gravitational flows under high energy flow regime and/or high depositional frequency. This flow regime has conditioned the distribution and composition of the burrowing benthic fauna, characterized by the dominance of burrows of stenohaline detritus-feeding organisms that inhabited well-oxygenated substrates, but showing low ichnodiversity. Cruziana and Skolithos ichnofacies show atypical composition if compared to their archetypal equivalents, possibly as result of the stress caused by the prevalence of high-energy conditions and/or of high-frequency deposition during the infill of the Los Palacios Basin in the early Eocene.

The ichnological record of the Capdevila Formation also revealed the shoaling-upward of the shallow slope deposits in the studied section culminating with the subaerial exposure of the substrate as consequence of a sea level drop. The reestablishment of the turbiditic deposition in the upper portion of the succession marks the subsequent base level rise and the return of the high-energy conditions and/or the high-frequency deposition in the basin.

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10. FIGURE CAPTIONS

Figure 1. A-B. Geographic location (A) of the study area (star) and its geological situation, near the Pinar fault (B), which demarcates the limit between the Los Palacios Basin and the Sierra de los Órganos, in western Cuba (modified from Albear and Iturralde-Vinent, 1985). C. Stratigraphy of the Los Palacios Basin showing the stratigraphic position of the Capdevila Formation (modified

from Brust et al., 2011). D. Architecture of the Los Palacios Basin during the Eocene, as estimated by Brust et al. (2011), showing the deposition of the Capdevila Formation and the potential sediment source areas.

Figure 2. Exposed siliciclastic deposits of the Capdevila Formation in Pinar del Río area, showing a general view of the lower portion (A) and the medium to upper portion (B) of the sedimentary succession described in this paper. Scales: 23 cm in A, 170 cm in B.

Figure 3. Schematic profile of the Capdevila Formation sedimentary succession in the study area signaling the trace fossil distribution and the bioturbation index (BI) per bed.

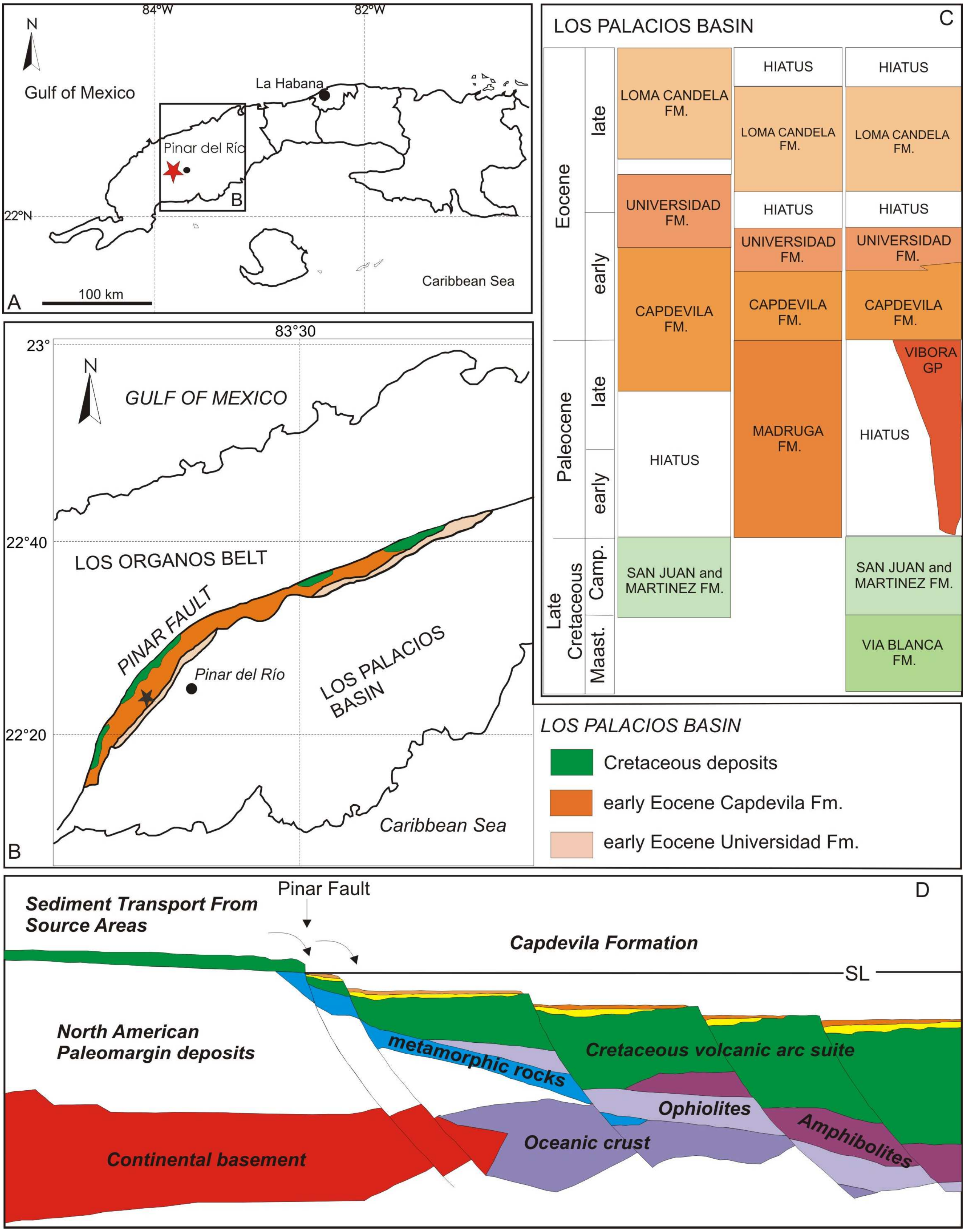
Figure 4. Sedimentary facies of the Capdevila Formation exposed in the study area. A. Massive sandstones capped by sandstones with parallel lamination and sandstones with ripples. B. Tabular beds of sandstones with parallel lamination. C. Sandstones with ripples. D. Tabular beds formed by interbedded siltstones and sandstones with parallel lamination. E. Fluidized sandstones and paraconglomerates. F. Massive sandstones. G. Wood fragment pavements in the sandstone beds. H. Fluidized sandstones. I. Paraconglomerates. Scales: 11 cm (A), 13 cm (B, F), 3.7 cm (C), 5 cm (D, H), 11 cm (E, I), 2 cm (G).

Figure 5. Ichnofabrics of the Capdevila Formation in the study area. A-B, *Asterosoma.* C. *Thalassinoides.* D-E, Rhizobioturbation. Scales: 2 cm.

Figure 6. Ichnofabrics of the Capdevila Formation in the study area. A-B. *Rhizocorallium*, showing the sharp walls with scratch marks. C-F. *Scolicia*, mainly represented by *Scolicia prisca* (C-E), *Scolicia var laminites* (Sl) and *Scolicia prisca* (Sp) (F). Scales: 2 cm.

Figure 7. Ichnofabrics of the Capdevila Formation in the study area. A. *Bichordites monastiriensis.* B. *Thalassinoides*. C-E. *Thalassinoides-Bichordites*, showing *Thalassinoides* (Th), *Palaeophycus* (Pa) and *B. monastiriensis* (Bm). F. *Ophiomorpha*. Scales: 2 cm, except for B, which measures 9 cm.

Figure 8. Schematic draw with reconstruction of the inferred sea level oscillation during the early Eocene in Los Palacios Basin, based on the trace fossil distribution in Capdevila Formation. A. Geomorphology of the Los Palacios Basin during the early Eocene (according to Sommer 2009 and Brust et al. 2011). The dashed square limits the estimated settings where the rocks exposed in the studied section were deposited. B. Turbiditic massive sandstone deposition in slope area with opportunistic (post-event) colonization represented by the *Ophiomorpha* ichnofabric. C. Sea level fall and debris flow deposition, represented by the paraconglomerate facies. D. Pre-event colonization in siltstones and sandstones deposited in the shelf-slope transition, represented by the *Asterosoma* ichnofabric. E. Post-event colonization in turbiditic parallel-laminated sandstones in shallow slope, represented mainly by the *Thalassinoides, Palaeophycus* and *Scolicia-Thalassinoides* ichnofabrics, and in shelf-slope transition deposits, represented by the *Bichordites-Thalassinoides* ichnofabric. F. Significant sea level fall (forced regression) and exposure of the shelf-slope transition zone, demarcated by the establishment of the Glossifungites Ichnofacies, represented by the *Rhizocorallium* suite and by rhizobioturbation. G. Sea level rising and the re-establishment of the turbiditic deposition with recurrence of post-event colonization in shallow slope settings, represented by the dominance of suites composed by the *Scolicia-Thalassinoides* and *Bichordites-Thalassinoides* ichnofabrics.


N
84°W
82°W
Gulf of Mexico
La Habana
Pinar del Río
B
22°N
Caribbean Sea
100 km
A
23°
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N
GULF OF MEXICO
22°40
LOS ORGANOS BELT
PINAR FAULT
Pinar del Río
LOS PALACIOS BASIN
22°20
Caribbean Sea
B
LOS PALACIOS BASIN
C
Eocene
late
early
Paleocene
late
early
Late Cretaceous
Camp.
Maast.
LOMA CANDELA FM.
UNIVERSIDAD FM.
CAPDEVILA FM.
HIATUS
SAN JUAN and MARTINEZ FM.
HIATUS
LOMA CANDELA FM.
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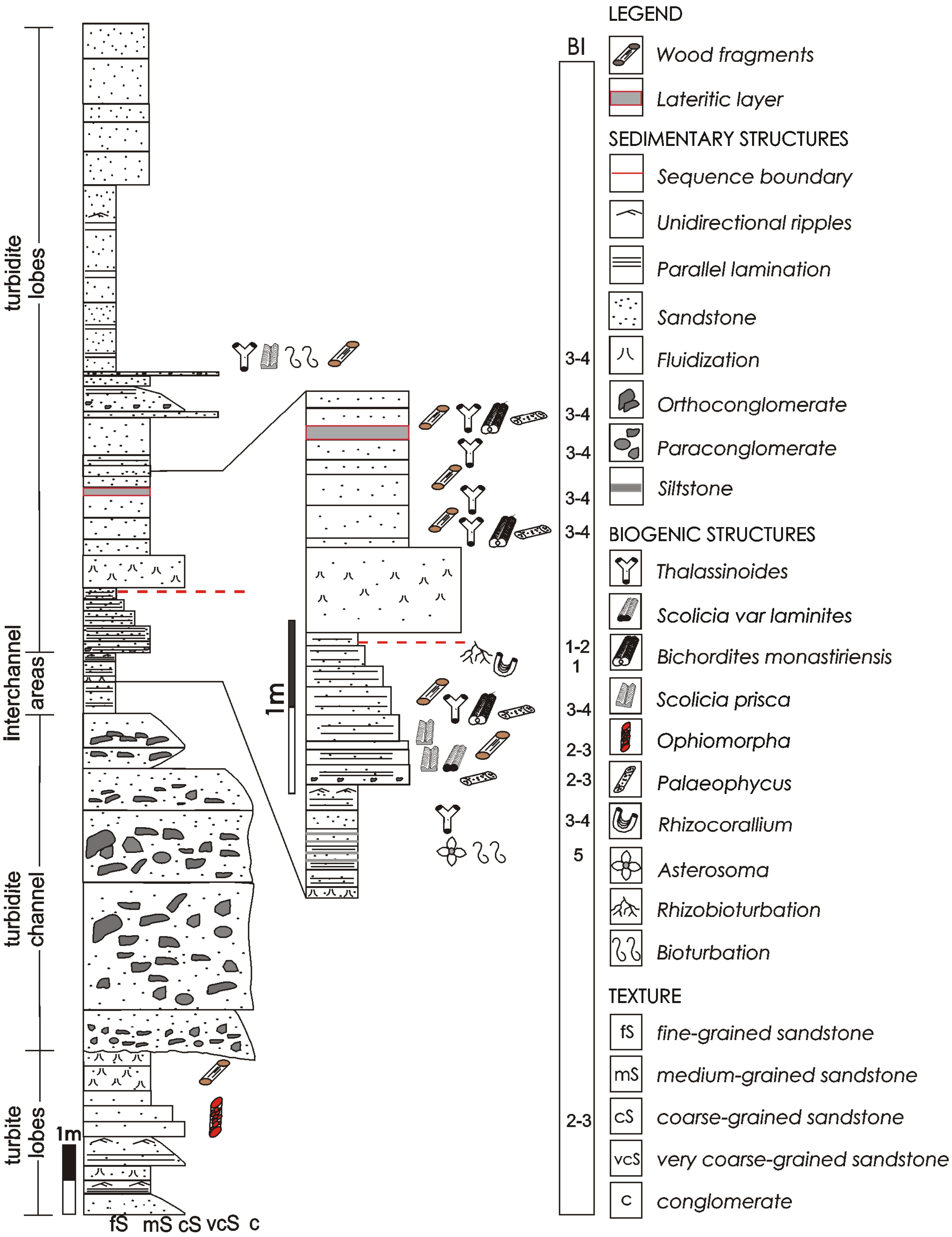
HIATUS
SAN JUAN and MARTINEZ FM.
VIA BLANCA FM.
LOS PALACIOS BASIN
Cretaceous deposits
early Eocene Capdevila Fm.
early Eocene Universidad Fm.
Sediment Transport From Source Areas
Pinar Fault
D
Capdevila Formation
SL
North American Paleomargin deposits
metamorphic rocks
Cretaceous volcanic arc suite
Ophiolites
Amphibolites
Oceanic crust
Continental basement

Figure.1

Figure 2


turbidite lobes
interchannel areas
turbidite channel
turbite lobes
1m
fS mS cS vcS c
1m
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3-4
3-4
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1
3-4
2-3
2-3
3-4
5
2-3
LEGEND
Wood fragments
Lateritic layer
SEDIMENTARY STRUCTURES
Sequence boundary
Unidirectional ripples
Parallel lamination
Sandstone
Fluidization
Orthoconglomerate
Paraconglomerate
Siltstone
BIOGENIC STRUCTURES
Thalassinoides
Scolicia var laminites
Bichordites monastiriensis
Scolicia prisca
Ophiomorpha
Palaeophycus
Rhizocorallium
Asterosoma
Rhizobioturbation
Bioturbation
TEXTURE
fS fine-grained sandstone
mS medium-grained sandstone
cS coarse-grained sandstone
vcS very coarse-grained sandstone
c conglomerate

Figure 3

Figure 4

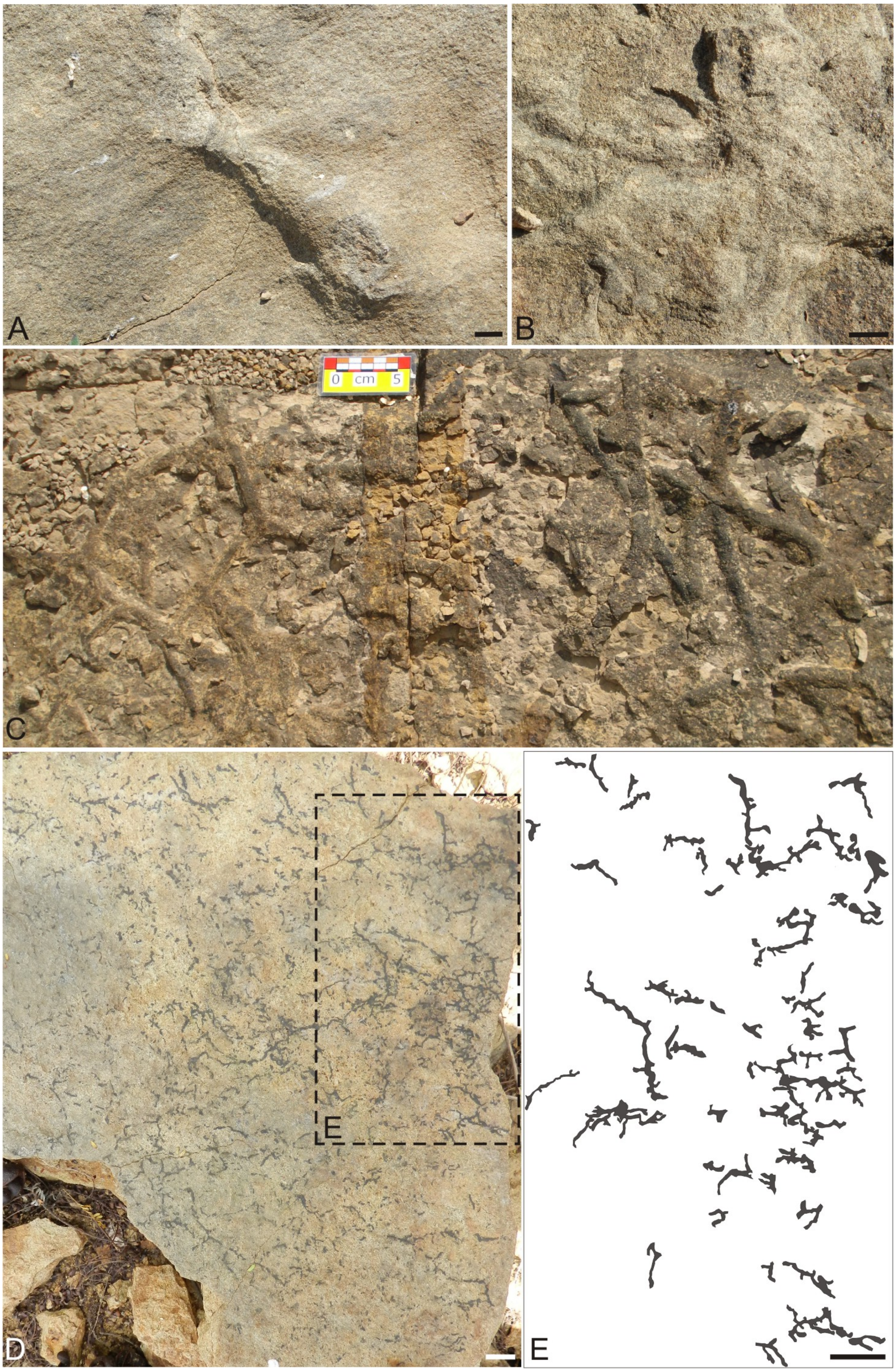

Figure 5

Figure 6

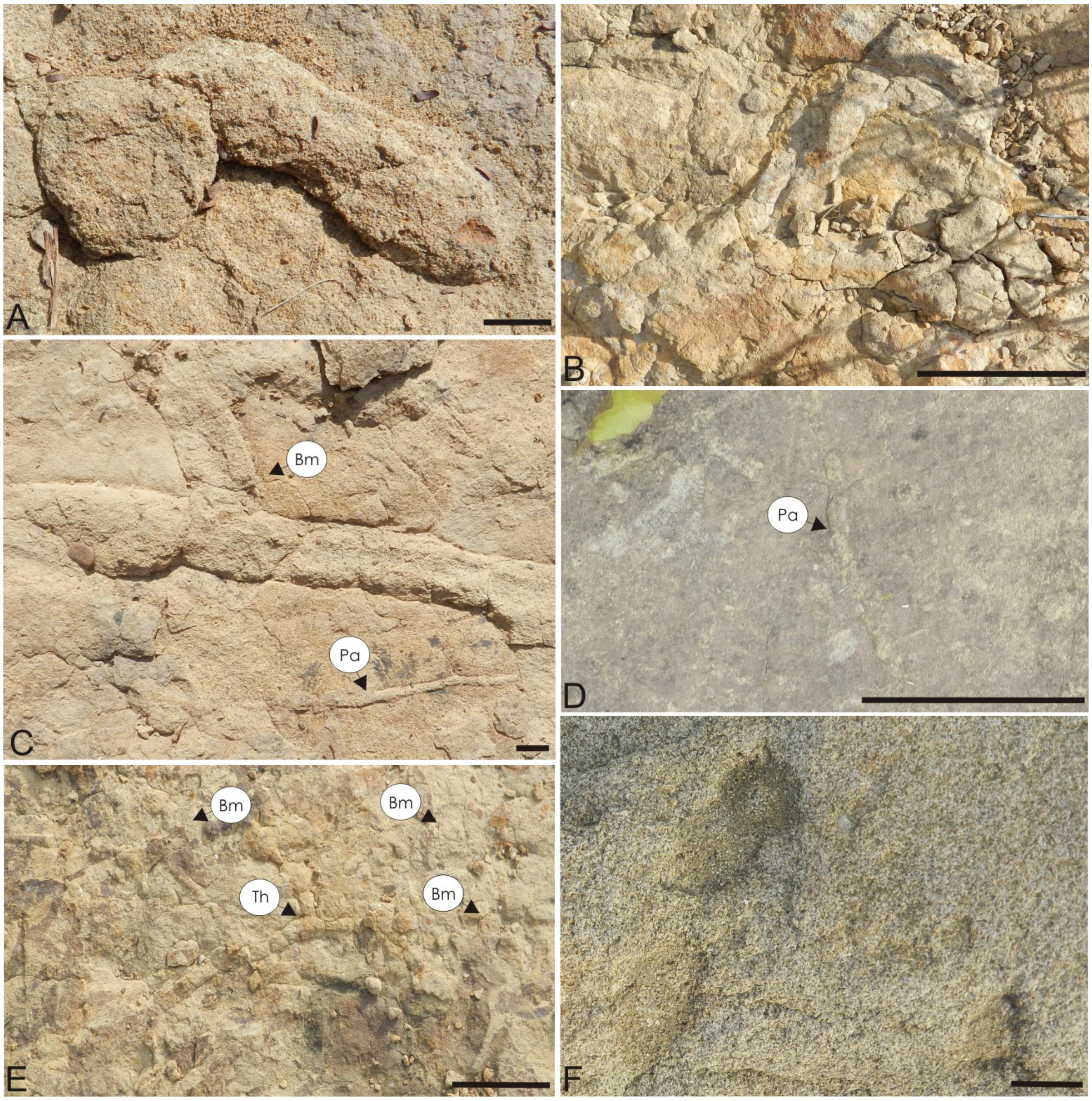

Figure 7

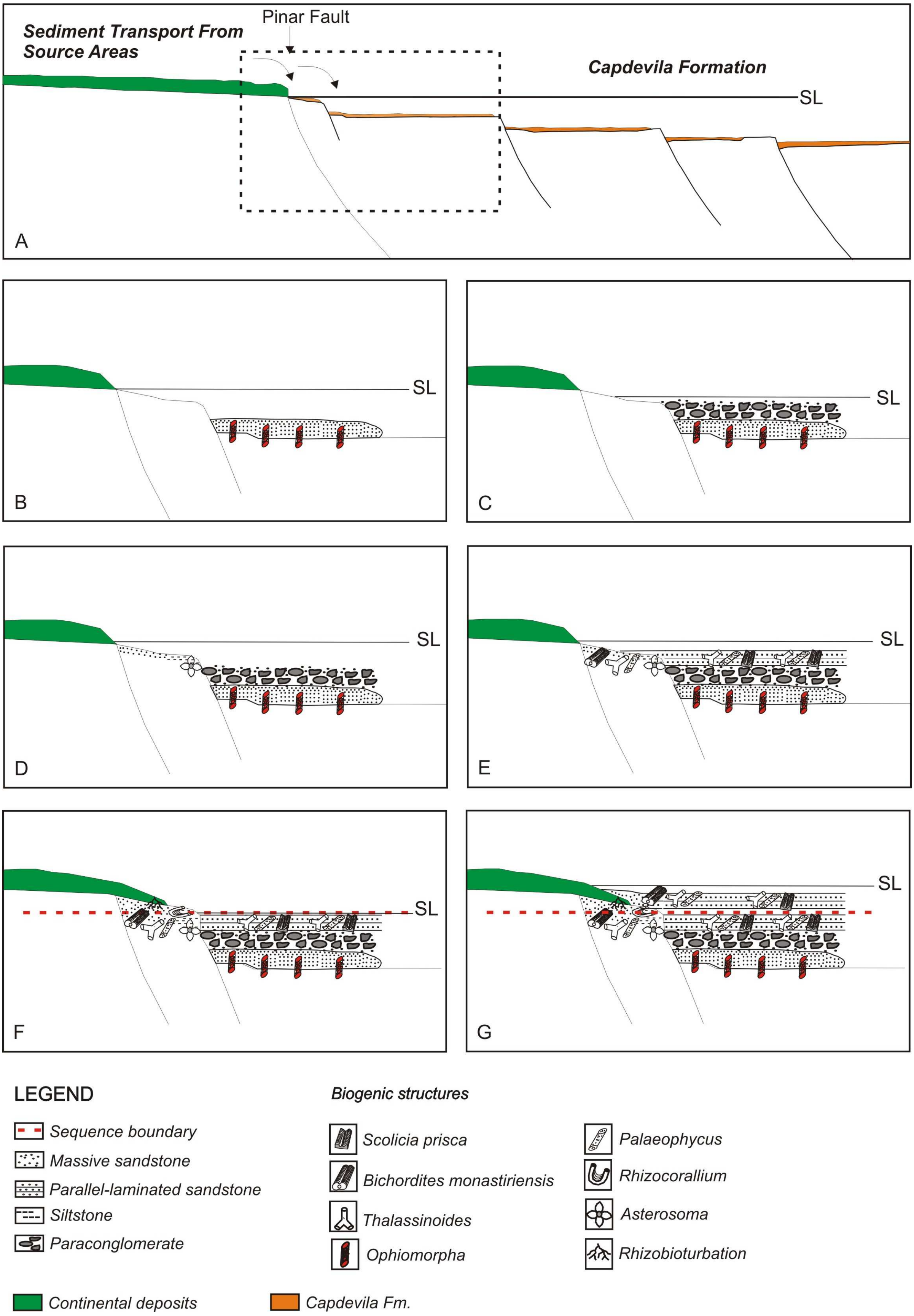
Sediment Transport From Source Areas
Pinar Fault
Capdevila Formation
SL
A
B
C
D
E
F
G
LEGEND
Sequence boundary
Massive sandstone
Parallel-laminated sandstone
Siltstone
Paraconglomerate
Biogenic structures
Scolicia prisca
Bichordites monastiriensis
Thalassinoides
Ophiomorpha
Palaeophycus
Rhizocorallium
Asterosoma
Rhizobioturbation
Continental deposits
Capdevila Fm.

Figure 8

6. CONCLUSÕES E CONSIDERAÇÕES FINAIS

O estudo dos icnofósseis pertencentes à Formação Capdevila, do Eoceno Inferior de Cuba ocidental, permitiu estabelecer os seguintes resultados:

Após análise do material encontrado no afloramento e daquele depositado na coleção, as estruturas com preenchimento laminado e duas faixas ou cordões de sedimentos foram associadas ao icnogênero *Scolicia.* As estruturas preservadas em epirrelevo negativo trilobadas foram incluídas em *Scolicia prisca.* Nos exemplares desta icnoespécie, foram encontradas variações na expressão dos meniscos nos bordos, no cordão dorsal central e nos cordões ou faixas de sedimentos, chegando a estar ausentes estas características em algumas partes das estruturas.

As estruturas em epirrelevo positivo que foram incluídas em *Scolicia* consistem de formas bilobadas com preenchimento laminado e são a variante preservacional *Scolicia var laminites*, exibindo variações no grau de expressão dos meniscos que constituem o preenchimento da escavação. Os dados obtidos, comparados com a bibliografia existente, permitiram observar que morfologias semelhantes a estas podem ser associadas atualmente também a táxons que caíram em desuso, pois foram sinonimizados.

Em relação ao espécime observado somente no afloramento, a presença de um cordão central em forma de coração e o preenchimento formado por meniscos permitiu sua identificação na icnoespécie *Bichordites monasteriensis*. Como o exemplar ora descrito provém do Eoceno Inferior de Cuba, ele representa o registro mais antigo conhecido desta icnoespécie. Além disso, são sugeridos equinodermos espatangoideos da Família Maretia como possíveis produtores destas estruturas em Cuba.

A integração da análise sedimentológica com a icnológica da sucessão sedimentar da Formação Capdevila, Bacia Los Palacios, permitiu propor deposição em talude pouco profundo, impactado por frequentes fluxos gravitacionais, principalmente fluxos turbidíticos. Esta condição paleoambiental resultou no estabelecimento de uma icnofauna de baixa icnodiversidade, principalmente estenohalina, típica de ambientes bem oxigenados e dominada por estruturas produzidas por organismos detritívoros. As suítes reconhecidas caracterizam as icnofácies Glossifungites, Cruziana e Skolithos, estas duas últimas atípicas em relação às suas equivalentes arquetípicas, como resultado do estresse ambiental causado pelas condições de alta energia e/ou alta frequência deposicional.

O registro icnológico e as suítes estabelecidas na sucessão estudada da Formação Capdevila refletem condições de raseamento até a ocorrência de exposição subaérea dos depósitos de talude, demarcando um evento de regressão forçada no Eoceno Inferior na Bacia Los Palacios. O posterior restabelecimento dos depósitos turbidíticos na porção superior da sucessão marca a subsequente subida do nível de base, com o restabelecimento e a manutenção das condições de alta energia e/ou alta frequência deposicional na bacia.

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