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Oxfordian–Berriasian Stratigraphy of the North American Paleomargin in Western Cuba: Constraints for the Geological History of the Proto-Caribbean and the Early Gulf of Mexico

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ABSTRACT

Many models that attempt to interpret the regional geology of the Caribbean-Gulf of Mexico area share the handicap of paying little attention to precise data from Cuba despite its location at the North American-proto-Caribbean paleoboundary. The North American Mesozoic paleomargin crops out along northern Cuba, an area where many wells have encountered Jurassic and Lower Cretaceous rocks. In this chapter, we present a stratigraphic interpretation of the North American passive continental paleomargin recognized in the Guaniguanico mountains (western Cuba) and identify the main geological events recorded in their Oxfordian to Berriasian sections. We correlate these sections with other Mesozoic passive paleomargin sections in Cuba, including the Escambray and Isle of Youth metamorphic terranes. These sections and those in the southeastern Gulf of Mexico record early stages of the disintegration of Pangea in Mesoamerica and the early development of the southeastern Gulf of Mexico and westernmost Tethys (proto-Caribbean). In all, two main sequences can be distinguished: (1) a lower terrigenous one and (2) an upper marine carbonate sequence. The transition from terrigenous to carbonate sedimentation occured during the late middle Oxfordian in western Cuba (and possibly in the Escambray mountains of central Cuba). In Placetas zone of central Cuba, the terrigenous-carbonate transition spans from Kimmeridgian to Berriasian. Transgression occurred close to the Kimmeridgian–Tithonian

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boundary. Deeper depositional conditions started during the Tithonian along the paleomargin in northern Cuba. This event may be correlated with the beginning of the drowning and stepback of the small carbonate platforms developed in the southeastern Gulf. Spreading and rifting ceased in the southeastern Gulf of Mexico when the Yucatan block reached its present position in the earliest Cretaceous. The unconformity that records the change in tectonic setting is called the late Berriasian surface, but our reinterpretation of biostratigraphic data indicates that the age of generalized flooding is middle Berriasian. In middle and late Berriasian times, a belt of deep-water carbonates surrounded the northern margin of the proto-Caribbean (westernmost Tethys). Extensive carbonate banks developed on the Bahamas-Florida platform and surrounded the emergent Yucatan Platform.

INTRODUCTION

Jurassic and Cretaceous sediments have been reported from Cuba since the 19th century, as shown on the map drawn in 1868 by Fernández de Castro (Hayes et al., 1901). Not until the mid-20th century, however, was there significant progress toward modern stratigraphic research regarding the Upper Jurassic and Lower Cretaceous, and this was mostly a result of oil exploration (Rigassi-Studer, 1963; Hatten, 1967; Pardo, 1975; Hatten et al., 1988, among others). Regional studies, such as those by Furrazola-Bermúdez (1964), Khudoley and Meyerhoff (1971), and Pardo (1975), reflect geological knowledge prior to the general acceptance of plate tectonics. Since the 1970s, three main factors have promoted the knowledge of Jurassic and lowermost Cretaceous stratigraphy in Cuba: (1) the introduction of plate tectonics theory; (2) geological surveys at scales of 1:250,000 for the whole country (Pushcharovsky, 1988) as well as of 1:100,000 and 1:50,000 for large regions; and (3) the drilling of many oil wells. Regional studies incorporating updated interpretations have been published since the late 1980s (Hatten et al., 1988; Cobiella-Reguera, 1996a, b, 1998, 2000; Iturralde-Vinent, 1996a, 2003, 2006; Millán Trujillo, 1997a, b, c; Alvarez Castro et al., 1998; Sánchez et al., 1998; Pszczolkowski, 1999; Moretti et al., 2003; Pszczolkowski and Myczyñski, 2003; Iturralde-Vinent and Lidiak, 2006; Pindell et al., 2006, among others). These provide relatively detailed data on the Cuban Jurassic and lowermost Cretaceous in relation to data available for other areas in the Caribbean and the Gulf of Mexico. Nevertheless, many models that attempt to interpret the regional geology (Ladd and Sheridan, 1987; Salvador, 1987; Winker and Buffler, 1988; Lewis and Draper, 1990; Pindell and Barrett, 1990; Stephan et al., 1990; Montgomery et al., 1992; Buffler and Thomas, 1994; Marton and Buffler, 1994; Pindell, 1994, among others) share the handicap of having little precise data from Cuba despite its location at the North American-proto-Caribbean paleoboundary. Therefore, its crucial importance for interpreting the geologic history in Mesoamerica has been overlooked (Cobiella-Reguera, 1996a, 2000; Pszczolkowski, 1999; Iturralde-Vinent, 2003; Pszczolkowski and Myczyñski, 2003; Pindell et al., 2006).

The North American Mesozoic paleomargin crops out across northern Cuba (Figure 1), an area where many wells have drilled into Jurassic and Lower Cretaceous rocks. Recent articles present several interpretations of the extent and composition of these rocks (Pszczolkowski, 1982, 1999; Echevarría-Rodríguez et al., 1991; Draper and Barros, 1994; Iturralde-Vinent, 1996a, 1997; Hutson et al., 1998, Cobiella-Reguera, 2000; Moretti et al., 2003; Pszczolkowski and Myczyñski, 2003, Schaffhauser et al., 2003, among others). This is when the Gulf of Mexico opened and widened, with oceanic lithosphere forming in the central part because of the Maya (Yucatan) block separation, rotation, and final emplacement (e.g., Marton and Buffler, 1994, 1999; Pindell et al., 2006). In this chapter, we present a stratigraphic interpretation of the North American passive continental paleomargin recognized in western Cuba (but see Pessagno et al., 1999; Pszczolkowski, 1999; Iturralde-Vinent, 2003; Pessagno and Martin, 2003; Pszczolkowski and Myczyñski, 2003, for rather different approaches) and identify the main geological events recorded in its Oxfordian to Berriasian sections. In addition, we evaluate correlations with other Mesozoic passive paleomargin sections in Cuba and offer some comments concerning regional stratigraphic correlations, especially involving the southeastern Gulf of Mexico.

STRATIGRAPHY

Upper Jurassic–Berriasian Rocks in Cuba

These fall into four basic groups (Figure 1):

1. The mainly sedimentary passive paleomargin sections of northern Cuba comprise three distinct areas (see below): western Cuba (Guaniguanico Cordillera), northern-central Cuba, and Maisí, in easternmost Cuba.

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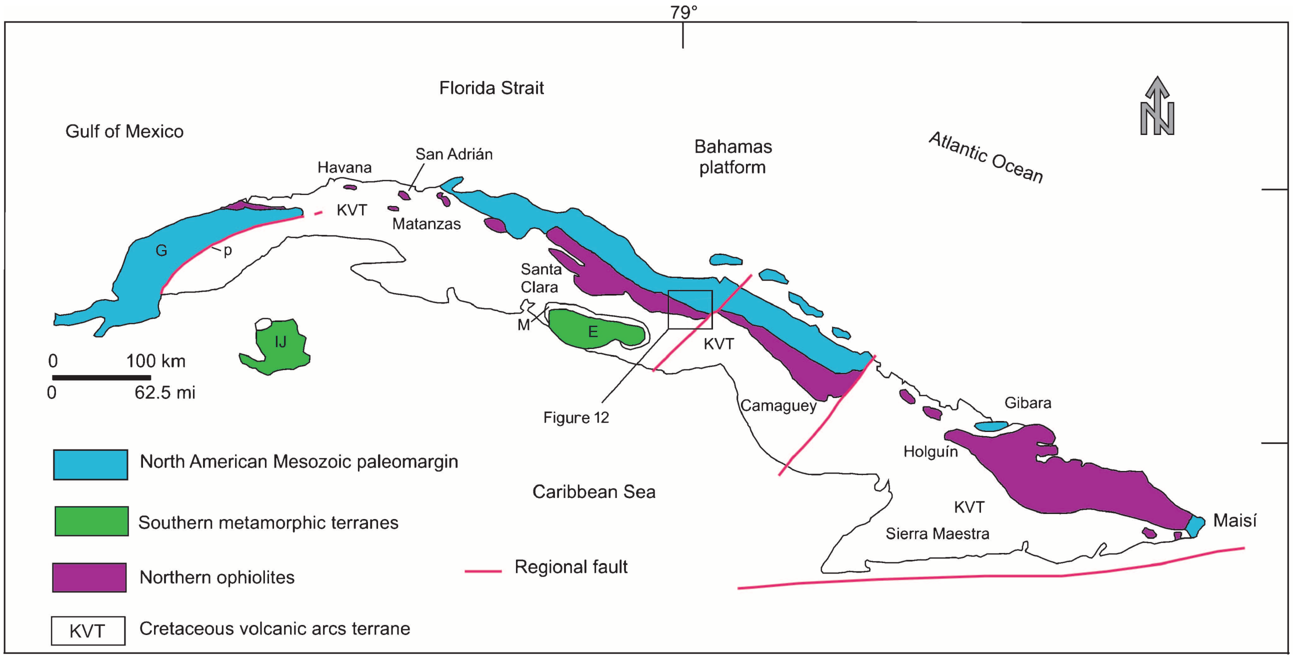

FIGURE 1. Mesozoic paleotectonic units of Cuba. G = Guaniguanico Cordillera; KVT = Cretaceous volcanic terrane; IJ = Isle of Youth (Isla de la Juventud); E = Escambray (Guamuhaya) massif; p = Pinar fault; violet areas: northern ophiolite belt; M = Mabujina complex. Note the inset for the location of Figure 12.

2. The Ophiolitic belt in northern Cuba, which comprises a huge mélange (Knipper and Cabrera, 1974; Cobiella-Reguera, 2005a; Garcia-Casco et al., 2006), is tectonically superposed on the Mesozoic paleomargin of northern Cuba. In the Ophiolitic belt, Andó et al. (1996), Iturralde-Vinent (1996a, b), and Llanes Castro et al. (1998) identified upper Tithonian to Albian rocks. Oxfordian rocks could be present in the ophiolites, considering their possible link with the fissure magmatism observed in the western Cuban paleomargin (Cobiella-Reguera, 1996a). The intense block tectonics and occurrence of transgressive pulses toward the end of the Middle Jurassic in the southwestern rim of the Gulf of Mexico Basin support the existence of deep waters in the region during the Late Jurassic interpreted by Schlager et al. (1984).
3. Successions are mainly composed of amphibolites and ultramafic rocks, which crop out most notably in the central Cuba Mabujina complex (Figure 1). The Mabujina complex not only is considered the oceanic basement of the Cretaceous volcanic terrane, but also includes some sections of metavolcanic arc rocks (Haydoutov et al., 1989; Millán Trujillo, 1996; Cobiella-Reguera, 2000; Pindell et al., 2006). Geochemical data have allowed some authors to interpret the Mabujina complex as mainly arc-derived metamorphic rocks (Grafe et al., 2001; Blein et al., 2003; Garcia-Casco et al., 2006). In general, this terrane rests tectonically on the ophiolites of northern Cuba. In south-central Cuba, the Mabujina complex and the Cretaceous volcanics rest, with tectonic contact, on the metamorphic Mesozoic successions of the Escambray (Guamuhaya) massif (Iturralde-Vinent, 1996a; Stanek et al., 2006).
4. Rocks of a southern extensional margin, subjected to Cretaceous metamorphism, are exposed on the Isla de la Juventud (Pinos) and the Escambray massif in southern central Cuba (Figure 1). Sedimentary protoliths of these southern metamorphic successions, commonly interpreted as terranes (e.g., Pszczolkowski, 1999; Iturralde-Vinent, 2003; Iturralde-Vinent and Lidiak, 2006; Pindell et al., 2006), are very similar to those of the Guaniguanico Cordillera (Furrazola-Bermúdez et al., 1964; Millán Trujillo, 1997a, b, c; Stanek et al., 2006, among others). Similarities suggest that Jurassic deposits in the three areas share a common origin; therefore, some authors have combined them within a single domain: the southwestern metamorphic terranes (Iturralde-Vinent, 1996a, 1997). Nevertheless, their actual tectonic positions are very different (Cobiella-Reguera, 1996a, 2000, see below) (Figure 1).

Only the passive continental margin type successions 1 and 4 are discussed in this chapter. Succesions 2 and 3 are discussed by Iturralde-Vinent (1996a, b), Cobiella-Reguera (2000, 2005a), Lewis et al. (2006), and Pindell et al. (2006), among others.

Upper Jurassic–Berriasian in the North American Paleomargin of Western Cuba (Guaniguanico Cordillera)

The low mountains of the Guaniguanico Cordillera contain the most extensive continuous outcrops of the North American Jurassic paleomargin in Cuba (Figure 2). To the south, the Guaniguanico successions are bounded by the Pinar fault, which separates them from the Cenozoic Los Palacios Basin. The largest and most impressive outcrops of alpine tectonics in the Greater Antilles are present in these highlands (Rigassi-Studer, 1963; Hatten, 1967; Piotrowska, 1978). To the northeast, the Guaniguanico section is covered by thrusted ophiolites and Cretaceous volcanic terranes (Pszczolkowski, 1994b; Cobiella-Reguera, 2000, 2005a). The Guaniguanico successions rest tectonically on sediments of the Gulf of Mexico (Iturralde-Vinent, 1996a; Gordon et al., 1997; Moretti et al., 2003). A thrust system divides rocks of the Guaniganico Cordillera into various tectonic units. Thrust sheets of the Sierra de los Organos comprise the lowest tectonic units, overridden by those of the Alturas Pizarras del Sur and Sierra del Rosario-Alturas de Pizarras del Norte (Figure 2). Minimum horizontal displacement of several tens of kilometers can be assumed between the lowest and highest units in the nappe pile (Cobiella-Reguera, 2005b). The age of the tectonic event is late Paleocene to earliest Eocene.

Throughout the Guaniguanico Cordillera, the Jurassic sections reveal (1) a lower part, composed almost entirely of slightly metamorphosed siliciclastic beds of the San Cayetano Formation high-pressure metasiliciclastic rocks, outcrops in the Cangre belt (Arroyo Cangre Formation, Figures 2, 3) (Somin and Millán 1981) and (2) mainly carbonate deposits rest on the siliciclastic section and extend to the Cretaceous. The upper San Cayetano Formation contains Oxfordian fossils, and thus the limit between the siliciclastic and carbonate successions is located within the Upper Jurassic. Oxfordian–Berriasian beds in western Cuba consist of sedimentary rocks and, to a lesser extent, igneous rocks that accumulated during the early drifting stage of Pangea and the formation of the proto-Caribbean (Pszczolkowski, 1999; Cobiella-Reguera, 2000, and references therein).

Figure 3 gives the Upper Jurassic–Berriasian stratigraphy in western Cuba, as updated in the present study.

San Cayetano Formation

The San Cayetano Formation is a terrigenous deposit (perhaps several thousands of meters thick in the most complete sections in Alturas de Pizarras) mainly composed of sandstones, siltstones, and claystones, with some conglomeratic beds (Haczewski, 1976; Pszczolkowski, 1978, 1999; Hutson et al., 1998) (Figure 4). Ore bodies with exhalative sedimentary sulfide mineralization (e.g., Valdés-Nodarse, 1998, and references therein) can be found in this unit. Thin discontinuous limestone horizons appear toward the top (Pszczolkowski, 1999) and no erosional discontinuity with the overlying carbonates is observed (Pszczolkowski, 1999, and references therein). At present, offering a detailed characterization of the terrigenous succession is impossible because of its homogeneity, the acute shortage of fossils, and tectonic complexity. The best stratigraphic approach is the facies pattern proposed by Haczewski (1976), who distinguished nine facies and interpreted deposition in the context of a widespread deltaic environment. Sierra de los Organos (SO) and at least part of the Alturas de Pizarras del Sur (APS) sections record fluvial, transitional, and shallow marine paleoenvironments (Figure 4a), whereas deeper water turbidites are present in Sierra del Rosario and Alturas de Pizarras del Norte (Figure 4b) (Haczewski, 1976; Cobiella-Reguera et al., 2000). Therefore, in Figure 2, the southwest corner of Alturas de Pizarras del Norte (APN) highlands is included in the APS tectonic unit (see also Figure 4a). Following Haczewski (1976) and (Cobiella-Reguera et al., 1997; Cobiella-Reguera, 2000) the authors believe that the formation accumulated in a major delta complex on a young passive continental margin during the proto-Caribbean early drift stage. Perhaps some sediment arrived from other sources located along an opposite margin, as suggested by preliminary studies on the mineral composition of San Cayetano sandstones (Pszczolkowski, 1986a; Cobiella-Reguera et al., 1997, 2000; Hutson et al., 1998; Rojas-Agramonte et al., 2008) and paleocurrent data (Haczewski, 1976). Total organic carbon (TOC) averages 1.1% (Moretti et al., 2003). Some authors consider the unit a synrift accumulation (Linares Cala, 1999; Moretti et al., 2003), but as Hutson et al. (1998) stated, neither the predominant quartz-rich sandstone composition (Pszczolkowski, 1986a; Cobiella-Reguera et al., 1997) nor the depositional architecture is suggestive of formation as a synrift unit.

The age of the San Cayetano Formation is controversial. A Triassic age was proposed by Iturralde-Vinent (2003) for the lower San Cayetano Formation, but no definitive Triassic fossils have been found. The oldest layers might be Early Jurassic (Areces-Mallea, 1991; Cobiella-Reguera, 1996b). The youngest beds are middle Oxfordian (Myczyñski and Pszczolkowski, 1976) (Figure 3) and contain *Perisphinctes (Dichotomosphinctes) cayetanensis*, *Perisphinctes (Dichotomosphinctes?) cf. anconensis*, and *Perisphinctes (Discosphinctes) pichardoi* in the Sierra del Rosario. Myczyñski et al. (1998) suggested that among the *Dichotomosphinctes* identified, forms such as *D. cayetanensis* may appear with a primitive morphology (Vertebrale-Antecedens chron in Europe).

Focusing on the Upper Jurassic, we are only concerned with the age of the upper part of the San Cayetano Formation. According to Myczyñski et al. (1998), the oldest horizons with ammonites contain morphologically

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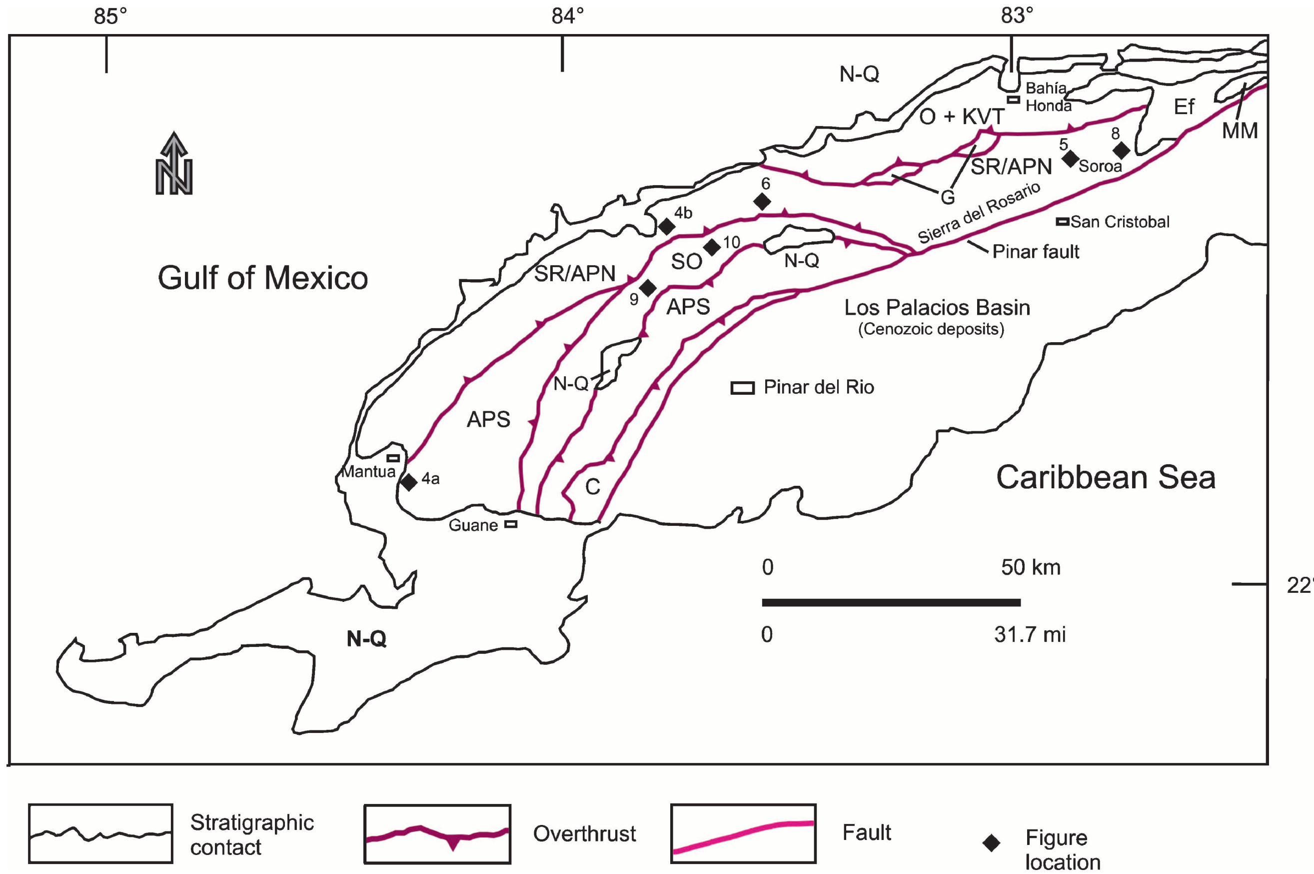

FIGURE 2. Tectonic map of the Guaniguanico Cordillera and its surroundings. N-Q = Neogene and Quaternary sediments; Ef = lower Eocene deposits (mainly turbidites); O + KVT = Cretaceous volcanic terrane + ophiolites; SR/APN = Sierra del Rosario-Alturas de Pizarras del Norte and Esperanza zone tectonic sheets; G = Guajaibón tectonic unit (Albian–Cenomanian carbonate bank); SO = Sierra de los Organos tectonic sheets; APS = Alturas de Pizarras del Sur tectonic sheet; C = Cangre belt; MM = Martín Mesa erosional window (outcrop of Sierra del Rosario sections). The ophiolites, the volcanic terrane, and the Guaniguanico units were emplaced during the Cuban orogeny of late Paleocene–early Eocene age in western Cuba. Los Palacios Basin is a Cenozoic structure. The locations of the outcrops in Figures 4–6, 8–10 are indicated by the corresponding numbers.

primitive *Dichotomosphinctes*, comparable with those from the Vertebrale-Antecedens chron in Europe, whereas the youngest horizons with ammonites contain morphologically innovative *Dichotomosphinctes* and probable *Gemmellarites* that belong to the Antecedens chron (European standard) of the middle Oxfordian. In other words, the ammonite-bearing stratigraphic interval within the Upper Jurassic of the San Cayetano Formation belongs to the lower–middle middle Oxfordian. Unfortunately, no ammonites have been found in the uppermost San Cayetano Formation, and thus, we cannot interpret the upper boundary of this unit at the ammonite zone-subzone level.

Francisco Formation

The Francisco Formation (Figure 3) crops out with a thickness of 13–25 m (43–82 ft) in the Sierra del Rosario and is composed of argillites and well-stratified micritic limestones, with fine intercalations of sandstones (Myczyñski, 1976a). According to Myczyñski and Pszczolkowski (1976), shales with calcareous concretions are present in the type locality, overlain by laminated limestones with thin shale beds (5 m [16 ft] thick), sandstones, and shales (2 m [6 ft]), and topped by shales with thin limestone intercalations. This formation contains the transition between the underlying terrigenous San Cayetano Formation and the overlying, mainly carbonate Artemisa Formation. The absence of the thin Francisco Formation in many sections might be caused by tectonic factors (shearing during thrusting). According to Myczyñski and Pszczolkowski (1976), water depth did not exceed 300 m (984 ft); Schlager et al. (1984) interpreted neritic deposition, and Pszczolkowski (1999) interpreted outer shelf deposits. We interpret that Francisco deposits accumulated at neritic depths under marine-restricted environments.

Two ammonite assemblages were identified in the Francisco Formation; the lower one with *Vinalesphinctes*,

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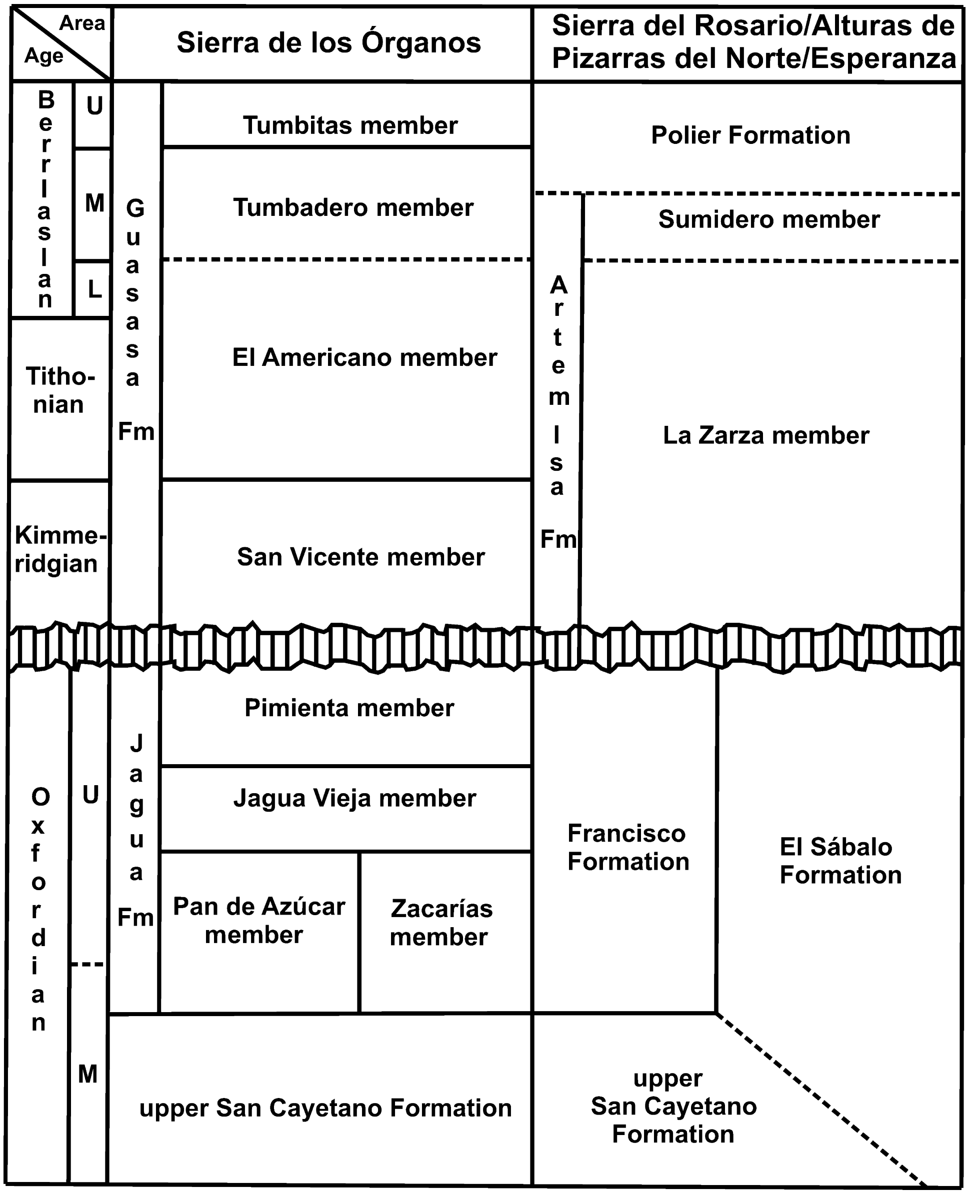

FIGURE 3. Schematic correlation chart of Upper Jurassic–Berriasian deposits in western Cuba. The main features of each lithostratigraphic unit are discussed in the chapter. U = upper; M = middle; L = lower.

Roigites, *Antilloceras*, *Cubaochetoceras*, and *Glochiceras*, and the upper one with *Euaspidoceras*, *Mirosphinctes*, *Cubaspidoceras*, and *Glochiceras*. Kutek et al. (1976) and Myczyñski (1976a, 1994) first interpreted these ammonite assemblages as indicative of late–middle and early–late Oxfordian age. Myczyñski et al. (1998) later reinterpreted the assemblages noting the predominance of *Vinalesphinctes* and *Cubasphinctes*, as well as "*Discosphinctes*" (= *Subdiscosphinctes*), *Ochetoceras*, *Cubaochetoceras*, and *Glochiceras*, and ancillary *Euaspidoceras*. These authors (1998, p. 198) assigned a Bifurcatus age to the assemblage dominated by *Vinalesphinctes* and *Cubasphinctes* in the Guaniguanico Cordillera in view of its correlation with the Chilean and North American findings of *Gregoryceras* and associated fauna (Gygi and Hillebrandt, 1991; Young and Oloriz, 1993). These findings have recently been extended to Mexico by Villaseñor et al. (2004). According to Myczyñski et al. (1998), the ammonite assemblages dominated by *Vinalesphinctes* and *Cubasphinctes* correspond to periods of strong endemism and can be correlated with the lower–upper Oxfordian in Europe. Particularly interesting for biogeography and relative paleogeography is the frequent occurrence of this ammonite assemblage in the Guaniguanico Cordillera (Francisco Formation in the Sierra del Rosario and Jagua Formation in the Sierra de los Organos) and its local, biostratigraphically coherent record in east-central Mexico (López-Palomino et al., 2006). Myczyñski et al. (1998) interpreted the upper assemblages with *Euaspidoceras* and *Mirosphinctes*, and with *Cubaspidoceras* and *Mirosphinctes* as early and middle Bimammatum chron, respectively (middle latest Oxfordian).

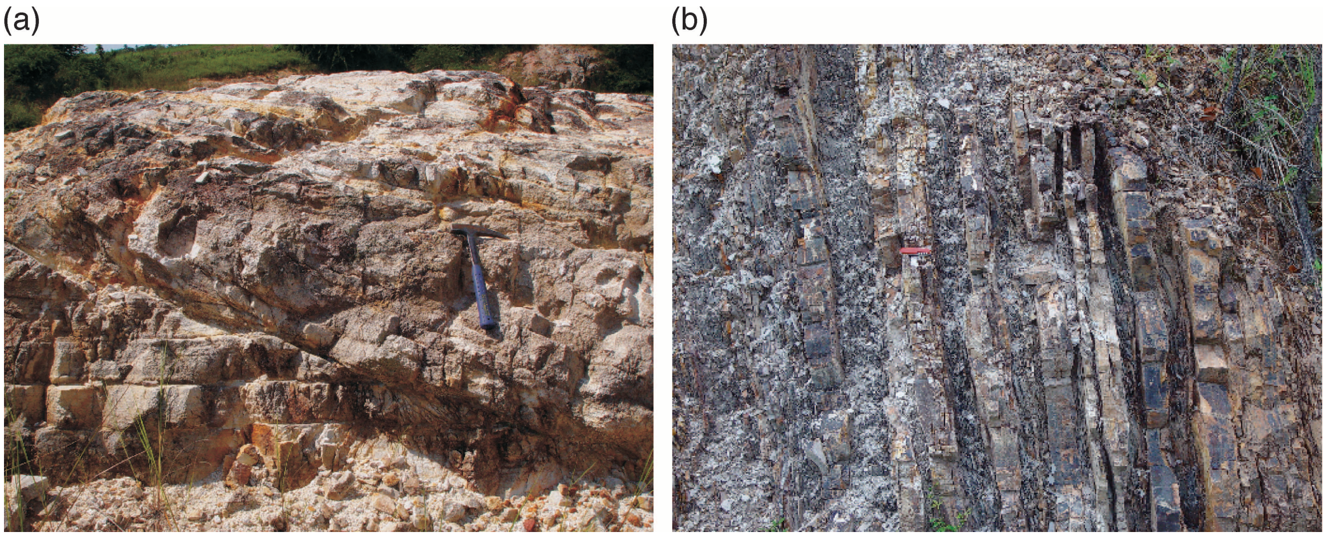

Figure 4. Outcrops of San Cayetano Formation. (a) Cross-bedded laminated quartzose sandstones at Veinte de Mayo, near the Guane-Mantua road (Figure 2). Cross-bedded sets attain several meters thickness. Some isolated well-rounded clasts 1–2 cm (0.3–0.6 in.) in diameter are present. The outcrop corresponds to Haczewski's (1976) facies A and belongs to Alturas de Pizarras del Sur unit. Coordinates: 22°12′51″N; 84°11′52.7″. (b) Well-bedded distal turbidites at Merceditas, Alturas de Pizarras del Norte, on the Viñales-Puerto Esperanza road (Figure 2). The sandstone interbeds increase to the right and become younger. Facies G in Haczewski's model. Coordinates: 22°41′30.4″ N; 83°44′0.7″.

El Sábalo Formation

Defined by Pszczolkowski (1994a) in the Sierra del Rosario, the El Sábalo Formation comprises successions dominated by mafic rocks (diabases, basalts, and, occasionally, gabbros) with several-meter-thick intercalations of well-stratified laminated siltstones, claystones, and black limestones with high organic content (Figure 5). El Sábalo Formation thickness can reach 400 m (1312 ft) (Cobiella-Reguera, 1996a, Iturralde-Vinent, 1996c, Pszczolkowski, 1999). Contacts are commonly tectonic, the upper one showing breccias locally (Pszczolkowski, 1999). Typically, carbonate intercalations appear only in the upper part of the El Sábalo Formation, whereas terrigenous layers are distributed throughout the succession. The presence of synsedimentary folds and faults involving mafites indicates that El Sábalo deposits were deposited on an inclined and/or episodically unstable bottom (Figure 5) (Cobiella-Reguera, 1996a). Deposition of the El Sábalo Formation on a poorly oxygenated bottom is accepted (Pszczolkowski and de Albear, 1983; Cobiella-Reguera, 1996a; Pszczolkowski, 1999), although the depositional environment was interpreted as continental slope (Cobiella-Reguera, 1996a) or outer shelf (Pszczolkowski, 1999). We interpret that low oxygenation is related to active magmatism and the pattern of marine currents in the area. As marine-restricted environments can be inferred for the coeval Francisco and Jagua formations, low oxygenation most probably was widespread, but it cannot be determined if it was basinwide with the information available.

Scarce microfossils are known from the El Sábalo Formation, although Pszczolkowski, (1994a) reported *Globochete alpina*, *Didemnoides moreti*, *Didemnoides* sp., *Didemnum carpaticum*, *Didemnum minutum*, ''*Colomisphaera*'' *cf. nagyi*, ''*Colomisphaera*'' *cf. pieniniensis*, and ''*Colomisphaera*'' sp. in carbonate horizons. We correlate the upper El Sábalo with the Francisco Formation (lower–upper Oxfordian). Supporting this interpretation

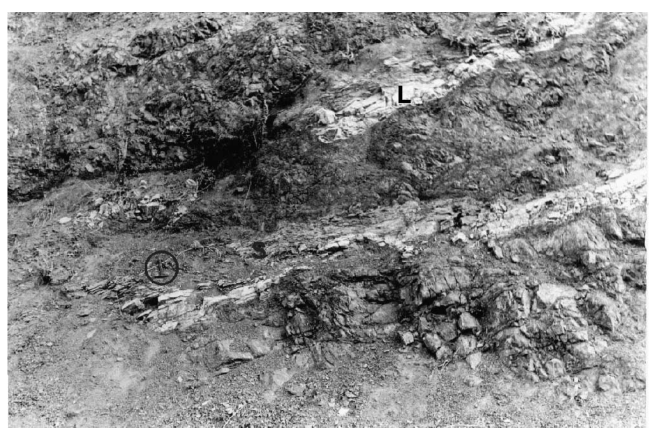

Figure 5. El Sábalo Formation outcrop in a road cut at the type locality (Figure 2). Massive dark rocks are diabases and laminated shales (s); the light ones are limestones (L). Note the broken limestone layer and the irregular sediments-mafite contact in some places, suggesting synsedimentary deformation. Hammer for scale, in circle. Coordinates: 22°49′16.4″N; 83°05′00″W.

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FIGURE 6. Well-bedded, slightly cherty, micritic dark, commonly laminated limestones of Artemisa Formation (Sumidero member) at Vega Nueva quarry, west of La Palma (Figure 2), Alturas de Pizarras del Norte. Strongly weathered foliated shale interbeds, 1–2 cm (0.3–0.6 in.) thick, constitute nearly 10% of the section. Terrigenous intercalations are more frequent in the Artemisa Formation than in coeval Sierra de los Organos sections. Coordinates: 22°44′02.5″N; 83°37′15.5″W.

are (1) microfossil horizons underlying the Artemisa Formation, the base of which is the upper Oxfordian Bimammatum zone (Kutek et al., 1976), probably Bimammatum subzone (Myczyñski et al., 1998), or younger as envisaged below (p. 11), and (2) the lithological similarity between limestones and claystones in the upper part of the El Sábalo Formation and the Francisco Formation. The lower, terrigenous El Sábalo Formation, without limestone beds, may also be correlative with the uppermost San Cayetano Formation (Cobiella-Reguera, 1996a). Although the upper and lower contacts are tectonic, the stratigraphic interval assumed for correlation should correspond to the Oxfordian interval that includes the upper San Cayetano and the Francisco formations (Figure 3). Yet, it is difficult to be conclusive with the data available. The occurrence of basalts in the Francisco Formation (Pszczolkowski, 1999, and references therein) reinforces this stratigraphic interpretation.

Cobiella-Reguera (1996b) correlated mafites of the El Sábalo Formation with the youngest diabase dikes reported from the Catoche knoll, in the southern Gulf of Mexico (Schlager, Buffler et al., 1984; Schlager et al., 1984). Based on the stratigraphic position assumed by Cobiella-Reguera (1996b), biochronostratigraphy as proposed by Myczyñski et al. (1998), and revisions of recent geochronology (UNESCO and IUGS, 2000 scale), the late intrusive phase recorded at Catoche knoll (160 Ma in Schlager et al., 1984; Schlager, Buffler et al., 1984) occurred earlier than the late Oxfordian magmatism recorded in the El Sábalo Formation. In fact, the youngest magmatic event in Catoche knoll can be placed at the latest Callovian (e.g., Hardenbol et al., 1998), or very close to the Callovian Oxfordian boundary, according to Witrock et al. (2003) (i.e., at 159.4 Ma). Therefore we assume some genetic asssociation of the magmatic phases in the El Sábalo Formation, and its related units in the Guaniguanico Cordillera, with the youngest intrusive rocks recorded in the southeastern Gulf (see below).

Artemisa Formation

This mainly calcareous unit represents the onset of a carbonate succession eastward in the Guaniguanico Cordillera (Sierra del Rosario). The bulk of the unit can be divided into two members: La Zarza and Sumidero. In the lower and middle part, the La Zarza member contains well-bedded and commonly laminated black micritic limestones with occasional intercalations of shales and siltstones. Pszczolkowski (1978) reported local interbeds of siltstones and fine-grained sandstones at the base of the Artemisa Formation and breccias, including shallow-water carbonate debris, from the lowermost horizons. Local occurrences of thick-bedded dolomitic limestones point to the restricted record of shallow-water San Vicente-type carbonates within the Artemisa Formation (Pszczolkowski, 1978). The upper La Zarza member contains bioclastic limestone horizons and some coquinas made up of ammonites and aptychi (Pszczolkowski, 1999). Calcareous beds with traces of distal turbidites gradually become laminated calcareous shale or marls upsection (Cobiella-Reguera, 1996b). Pszczolkowski (1978) reported horizons with folds and submarine slide breccias, and layers of detrital limestones with shallow-water elements (e.g., ooids, *Favreina*) intercalated in pelagic deposits. The upper Artemisa Formation (Figure 6) is characterized by cherty horizons with abundant radiolaria, which are used to identify the Sumidero member. Pszczolkowski (1978, 1999) reported pink and light-brown limestones in this upper member, but coloration may be caused by alteration by groundwater, and the original sediments might well be dark, like the remaining rocks in the formation.

Paleoenvironments in the lower La Zarza beds are little studied. Pszczolkowski (1999) proposed that dolomitized limestones in the lower La Zarza member might have accumulated in partially restricted coastal lagoons, whereas the upper part of this unit was deposited on the outer shelf. For the Sumidero member, this author interpreted a pelagic deposit accumulated below the aragonite compensation depth. However, the presence of sediments with the above-described turbiditic features in upper La Zarza member beds and the occasional occurrence of synsedimentary breccias and folds (Pszczolkowski, 1978; Myczyñski and Pszczolkowski, 1994; Cobiella-Reguera, 1996b) suggest basin and probably local slope conditions late in the Tithonian, according to the Wilson (1980) model. The context suggests external

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zones of a carbonate ramp that deepened during the Late Jurassic and earliest Cretaceous. Indeed, as usually interpreted, the La Zarza member contains late Oxfordian sediments (but see below), albeit little biostratigraphic data below the Tithonian exist. Thus, lacking significant data on facies changes in the La Zarza member, we can only identify deepening that provided a favorable environment for ammonites that accumulated in deposits close to the Kimmeridgian–Tithonian boundary in the eastern Guaniguanico Cordillera. Assuming deepening during the Late Jurassic–Early Cretaceous would then be appropriate. The undisturbed horizontal laminations in many beds and the lack of bioturbation and benthic autocthonous fauna, together with the dark color in nonweathered rock surfaces (high values of TOC are reported by Moretti et al., 2003, for the Sumidero member), clearly point to deposition in poorly ventilated, dyssaerobic to anoxic bottoms, although no conclusive interpretation of water depth is available.

The basal Artemisa Formation contains late Oxfordian ammonites (Kutek et al., 1976), found only at the type locality of the Francisco Formation, near Cinco Pesos, Sierra del Rosario. In two beds of marly nodular limestones, separated by a thin layer of marly shales, and lying on Francisco Formation shales, Kutek et al. (1976) reported a poorly preserved ammonite assemblage containing *Mirosphinctes* and *Cubaspidoceras*, for which they envisaged not to be post-Bimammatum age. The age of this ammonite assemblage was interpreted as middle Bimammatum chron by Myczyñski et al. (1998). According to literal translation of Kutek et al. (1976, p. 305), "...most of the ammonites are preserved as incomplete moulds and imprints, which suggest solution and mechanical destruction of shells in deposits. Voids originating from solution of primary organic structures are sometimes filled with coarse secondary calcite." In one locality (ibid. p. 306) "...a layer of the ammonite bearing limestones is directly overlain by a dolomite sediment yielding tubular phosphatic pellets, a few mm in size, possibly of organic origin (?coprolites)." A little higher in the section, these authors quoted "...a layer... with numerous fissures...infilled with sparry dolomite with numerous phosphatic structures... and small borings, possibly made by polychaetes." "A bed with numerous fissures, infilled with sparry dolomite, with numerous phosphatic structures and small borings, possibly made by polychaetes." Kutek et al. (1976) concluded that the observed phenomena are evidence of starved deposition, including breaks in sedimentation. Also near Cinco Pesos, in beds possibly only a little higher in the section, one of us (J. L. Cobiella-Reguera) sampled the following assemblage (identified by J. Fernández-Carmona and S. Blanco-Bustamante): *Colomisphaera nagyi*, *Stomiosphaera moluccana*, *Globochaete alpina*, *Cadosina aff. parvula*, and *Cadosina fusca*. Fernández-Carmona and Blanco-Bustamante interpreted this association as Kimmeridgian, although according to Fernández Carmona and Pendás Amador (1998), *C. fusca* is more likely a Tithonian species. These findings suggest that additional research is necessary to establish the age of beds in the lowermost La Zarza member, perhaps entailing a redefinition of the lower boundary of the unit, excluding the two basal limestone beds with ammonites, which could be assigned to the Francisco Formation, because of their unconformable contact with the overlying beds (Figure 3).

In the upper La Zarza member, successive assemblages of ammonites are characterized by *Parakeratinites*, *Hybonoticeras*, *Pseudolissoceras*, *Lytohoplites*, and *Micracanthoceras-Corongoceras* or *Durangites-Himalayites-Salinites*, as well as tintinnoids (*Chitinoidella* and *Crassicollaria*), identified and correlated by Myczyñski and Pszczolkowski (1994) and Myczyñski (1999). These authors interpreted the upper La Zarza member as Tithonian and the overlying cherty deposits of the Sumidero member as Berriasian. Similarly, Pszczolkowski (1999) placed the boundary between the La Zarza and Sumidero members, which marks the onset of siliceous sedimentation, at the Jurassic–Cretaceous (Tithonian–Berriasian) boundary. Previously, however, Myczyñski (1989, his figure 2) and Myczyñski and Pszczolkowski (1990, their table 1) suggested that the La Zarza member and the El Americano member (see below) might include Berriasian rocks. According to our comments on the El Americano member in the Guasasa Formation (Sierra de los Organos) (see also Pszczolkowski et al., 2005), which were based on Tavera et al. (1994), Olóriz et al. (1995), and an updated interpretation of calpionellids (Myczyñski, 1989; Myczyñski and Pszczolkowski, 1994), we agree with the assignment of an early Berriasian age (see below) in the La Zarza member. The finding of *Stomiosphaerina proxima* and *Calpionella elliptica* in the upper La Zarza member, near Soroa, is also significant (Figure 7). This could extend the age to the middle Berriasian if the citation of *C. elliptica* did not involve known homeomorphs from the late Tithonian and earliest Berriasian. In addition, no precise calpionellid biostratigraphy from the Sumidero member has been published. Preliminary data compiled by Pszczolkowski (1978, his table 6) and data in Figure 7 indicate that the late middle Berriasian (uppermost B to C calpionellid zones) is recognized from lower but not the lowermost horizons in this member containing *C. elliptica*, probable *Remaniella*, and *Calpionellopsis*. Although Pszczolkowski (1999) interpreted the youngest Sumidero deposits as Valanginian in age, the precise identification of the first intercalated sandstones of the overlying Polier Formation in the eastern Sierra del Rosario (Figure 7) suggests that they did not range above the Berriasian. In the senior author's experience, the Valanginian sections at Sierra del Rosario contain significant amounts of sandstones and therefore belong to the Polier Formation.

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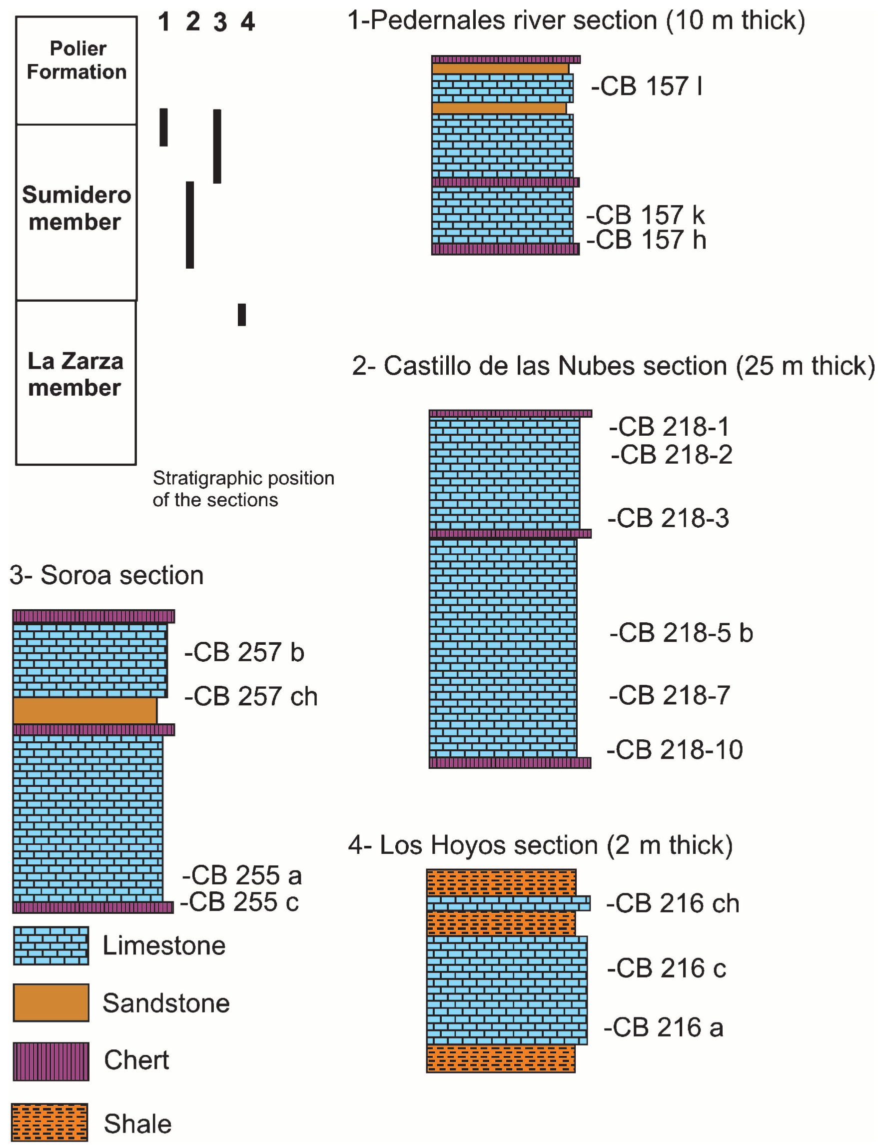

Figure 7. Schematic stratigraphic columns in upper Tithonian–Berriasian sections around Soroa (Figure 2) in southeastern Sierra del Rosario, Guaniguanico Cordillera, western Cuba. Black bars beside the general column represent the stratigraphic thickness of each minor column. Samples (CB). Pedernales river section: Artemisa Formation (Sumidero member): CB 157 h = *Tintinopsella carpathica*, *Calpionella alpina*, *Stomiosphaerina proxima*, *Crassicollaria* sp.?; CB 157 k = *Calpionella* sp., calcareous calpionellids; Polier Formation: CB 157 l = *Cadosina fusca*, *Stomiosphaerina proxima*, *Calpionella alpina*, *Tintinopsella* sp., *Calpionella cf. C. elliptica*. Castillo de las Nubes section: Artemisa Formation (Sumidero member): CB 218-10 = *Tintinopsella longa*, *Calpionella alpina*, *Stomiosphaerina proxima*, calcareous calpionellids; CB 218-7 = *Tintinopsella carpathica*, *Calpionella alpina*, *Stomiosphaerina proxima*, calcareous calpionellids; CB 218-5b = *Calpionella alpina* (small forms), *Tintinopsella carpathica*, *Calpionella elliptica*, *Nannoconus* sp.; CB 218-3 = *Calpionella elliptica*, calcareous calpionellids, *Nannoconus* spp.; CB 218-2 = *Tintinopsella longa*, *Calpionella alpina* (small forms), *Stomiosphaerina proxima*, calcareous calpionellids, *Nannoconus* spp.; CB 218-1 = *Tintinopsella longa*, *Calpionella alpina* (small forms), *Stomiosphaerina proxima*. Soroa section: Artemisa Formation (Sumidero member): CB 255 c = *Tintinopsella* sp., *Calpionella* sp., calcareous calpionellids; CB 255 a = *Calpionella* sp., calcareous calpionellids; CB 257 ch = *Calpionella alpina*, *Tintinopsella* sp.; Polier Formation: CB 257 b = *Tintinopsella carpathica*, *Calpionella alpina*, *C.* sp., *Colomisphaera* sp., *Crassicollaria* sp., *Crustacadosina* sp. Los Hoyos section: Artemisa Formation (La Zarza member): CB 216 a = *Colomisphaera carpathica*, *Cadosina fusca*, *Didemnoides moreti*, *Saccocoma* sp.; CB 216 c = *Saccocoma* spp., *Colomisphaera* sp., *Cadosina* sp.; CB 216 ch = *Stomiosphaerina proxima*, *Calpionella cf. C. elliptica*. Paleontologist: José Fernández-Carmona.

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Polier Formation

Conformably overlying the Artemisa Formation, the Polier Formation comprises a succession of well-bedded, commonly laminated dark limestones with intercalations of sandstones, siltstones, and claystones (Figure 8) (Cobiella-Reguera et al., 1997; Pszczolkowski 1999). Limestones include common radiolarian-rich horizons, as well as turbiditic ones with bioclasts derived from shallow-water environments. Thin cherty horizons occur at the bottom of the unit and, locally, at the top. Terrigenous beds are silica-rich distal turbidites (Cobiella-Reguera et al., 1997; Pszczolkowski, 1999), which are much more frequent in the northern sections in the Sierra del Rosario and its western prolongation (Esperanza zone). As these thrust sheets contain sections originally located to the south (Cobiella-Reguera et al., 2000), a source of terrigenous continental deposits was probably active from the south. This contrasts with the southward dominant trend in paleocurrents reported by Pszczolkowski (1978) and Cobiella-Reguera et al. (1997). The Polier Formation represents deposition in a deep-water carbonate environment above the calcite compensation depth, receiving siliciclastic turbidites more or less mixed with shallow-water carbonates (Pszczolkowski, 1982, 1999; Cobiella-Reguera et al., 1997). The fine undisturbed laminations, dark color, and absence of autocthonous benthic fauna all clearly point to accumulation on dysaerobic to anoxic bottoms, but conclusive data about water depth are unavailable for these open-sea deposits. Pszczolkowski (1999) attributed a late Berriasian age to the lowermost Polier Formation on the basis of previously reported calpionellids (Pszczolkowski, 1978, his table 6). In horizons close to the base, Fernández-Carmona and Blanco-Bustamante identified *Tintinnopsella carpathica*, *Calpionella alpina*, *C. elliptica*, *Crassicollaria* sp., and *Calpionellopsis simplex* (Figure 7). Reference to these species does not include data on the relative abundance or possible species successions, so evaluating their interpretations is difficult. We cannot rule out the possibility that horizons belonging to the latest–middle Berriasian may be represented, too. In addition, a revision of data available to the senior author indicates that the latest–middle Berriasian and mainly the early–late Berriasian are recognized in the lowermost Polier Formation (Figure 7). In fact, our most recent revision of calpionellids indicates latest–middle Berriasian (upper C zone) and mainly early–late Berriasian (D1 and undifferentiated D zones) for the lowermost Polier Formation based on the first appearance datum (FAD) of *Tintinnopsella longa* together with *C. simplex*, *Calpionellopsis* sp., *Remaniella* sp., and *Calpionella* sp. cf. *elliptica*. Pszczolkowski (1999) held the lower boundary of Polier Formation to be diachronous, but no biostratigraphic data were given to support this claim. Pszczolkowski and Myczyñski (1999, 2003) considered the top of the Polier Formation to be Aptian in age.

FIGURE 8. Detail of Polier Formation outcrop in the upper San Juan River Valley, north of Las Terrazas, easternmost Sierra del Rosario (Figure 2). The white composite bed is a slightly weathered limestone. The upper laminated part shows flat isolated ripple marks and is separated from the lower structureless and radiolaria-nannoconid-rich mudstone by a stylolitic suture, most probably related to an erosion surface. Overlying dark rocks are sandstones and shales (turbidites). Coordinates: 22°51′54.5″N; 82°56′44.5″W.

Jagua Formation

This unit, in the Sierra de los Organos, contains a 160-m-thick (525-ft-thick) carbonate succession of dark (TOC average 0.9%) (Moretti et al., 2003) wackestones and packstones with a variable amount of clayey sediments (Figure 3). The formation is commonly subdivided as follows: at the base, the Pan de Azúcar member (coquinas and bioclastic or black oolitic limestones) and the Zacarías member (argillites and black siltstones with scarce ammonites); in the middle, the Jagua Vieja member (claystones and marly limestones with calcareous concretions [“quesos”] containing a variety of ammonites and marine vertebrates); and at the top, the Pimienta member (well-stratified micritic limestone with some layers of claystones) (Pszczolkowski, 1978). Judoley and Furrazola-Bermúdez (1965) recognized conglomerates and breccias at the bottom of their sequences, overlying upper Oxfordian deposits dated with ammonites. Some authors have interpreted breccias atop the Jagua Formation, at the boundary with the Guasasa Formation (Figure 9), as evidence of synsedimentary tectonic activity of variable intensity (Hatten, 1967; Judoley and Furrazola-Bermúdez, 1968; Khudoley and Meyerhoff, 1971), whereas others evoke a tectonic origin (Knipper and Puig, 1967). Pszczolkowski (1999) found evidence of local erosion prior to deposition of shallow carbonates at the base of the Guasasa Formation (San Vicente member). The Jagua Formation is assumed to be a neritic deposit (Pszczolkowski, 1978, 1999) in which the Zacarías member accumulated under deltaic influence, whereas the remaining members might have accumulated on a carbonate ramp (Cobiella-Reguera, 1996b), from very

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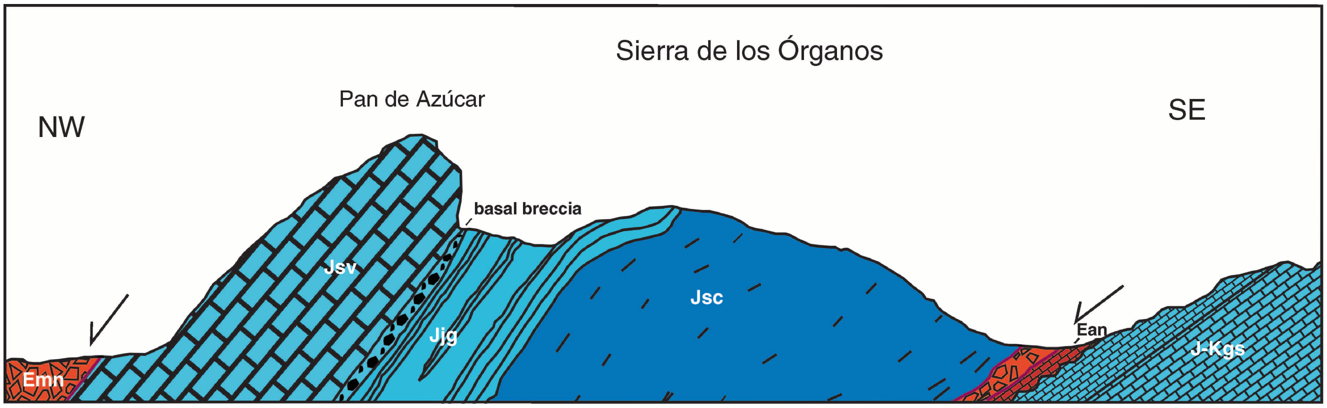

FIGURE 9. Profile across Pan de Azúcar area in Sierra de los Organos (modified from Hatten, 1967). The names of the stratigraphic units are used in the present chapter. Jsc = San Cayetano Formation; Jjg = Jagua Formation; Jsv = San Vicente member (lower Guasasa Formation); J-Kgs = Guasasa Formation; Ean = Ancón Formation (upper Paleocene); Emn = Manacas Formation (upper Paleocene?–lower Eocene). Observe the breccias at the base of San Vicente member. Not to scale. Section length: about 2 km (1.2 mi). The location is in Figure 2.

shallow waters near carbonate shoals for the Pan de Azúcar member to somewhat deeper water for the Jagua Vieja member and middle to outer shelf deposits for the Pimienta member (Pszczolkowski, 1978, 1999). All the members were deposited on poorly oxygenated sea floors. Similar to the Francisco Formation in the Sierra del Rosario, but thicker, the Jagua Formation represents the transition from terrigenous successions of the San Cayetano member to San Vicente member carbonates in the Guasasa Formation (Sierra de los Organos). Metamorphic equivalents of the Jagua Formation, with ammonites, have been reported from the Cangre belt (Somin and Millán, 1981).

The age of the Jagua Formation has been estimated on the basis of ammonites, except for the Pan de Azúcar member, which has traditionally been correlated with the Zacarías member. Ammonites have been collected since the beginning of the 20th century (e.g., Judoley and Furrazola-Bermúdez, 1968; Myczyñski, 1976a, b; Wierzbowski, 1976, and references therein). The classic article by Judoley and Furrazola-Bermúdez (1968) does not include precise biostratigraphy. Myczyñski (1976a, 1994) and Wierzbowski (1976) provided biostratigraphic interpretations based on their correlation with the European standard. These authors attributed a middle Oxfordian age to assemblages containing mainly *Vinalesphinctes* and *Cubasphinctes* (in the Jagua Vieja and the Zacarías members, according to Wierzbowski, 1976, his table 2) and late Oxfordian (especially in the Pimienta member) to those dominated by *Mirosphinctes* and *Cubaspidoceras*. On the basis of a precise correlation with data obtained from Chile, southern North America, and the western Tethys, Myczyñski et al. (1998) concluded that ammonites from the Jagua Formation range from the Bifurcatus to pre-latest Bimammatum chrons. The Pan de Azucar member has been stratigraphically correlated with the Zacarias member (early Bifurcatus age, according to Myczynski et al., 1998) but no ammonites have been found, and outcrops limitations exists (tectonics; to compare De La Nuez, 1972, 1974, and Wierzbowski, 1976). In addition, the bioclastic, oolitic and ammonites-free Pan de Azúcar member could either mask hiatuses or include late Transversarium chron deposits (Figure 3); alternatively, it could not include sediments younger than this age (e.g., stratigraphical gap at the top). The latter interpretation (not included in Figure 3) provides an alternative to traditional ones, and is based on the fact that occurrences of Zacarias Mb seem to be related to thinner Jagua Vieja member deposits (e.g., Myczyñski, 1976; Figures 5–6, p. 264)-i.e., The Pan de Azúcar member seems to be unrelated to stratigraphic changes in Zacarias and Jagua Vieja members and, therefore, unconnected to environmental-depositional dynamics during the Bifurcatus Chron ammonite-bearing deposits. Whatever the case, and before detailed sedimentology of Pan de Azúcar member be available, the lack of ammonites in the Pan de Azúcar member and uppermost San Cayetano Formation impedes approaching more conclusive interpretations.

The correlation of the upper boundary of the Jagua Formation, i.e., the top of the Pimienta member, cannot be established accurately because of the absence of ammonites in the uppermost Pimienta member. The interpretation is further complicated by the fact that the overlying facies (San Vicente member in the Guasasa Formation) is devoid of ammonites. Therefore, we can only establish the age of the youngest ammonite-bearing horizons in the Jagua Formation (pre-uppermost Pimienta member), which Myczyñski et al. (1998) established as within-Bimammatum chron (probably Bimammatum subchron). The age of the uppermost Jagua Formation could then be younger than Bimammatum subchron.

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However, the absence of Planula zone ammonites (uppermost Oxfordian or lowermost Kimmeridgian) and the supporting occurrence of conglomerates and breccias in many basal outcrops of the overlying San Vicente member would indicate erosion or nondeposition of latest Oxfordian beds in the Pimienta member of the Jagua Formation We envisage a correlation between this erosional (or non depositional) episode and the interval of starved (or condensed) sedimentation in the lowermost Artemisa Formation (see above). In Figure 3, an unconformity is assumed between the Pimienta and San Vicente members, together with a late, but not latest, Oxfordian age (Planula chron) for the youngest beds of the Pimienta member in the Jagua Formation.

Guasasa Formation

In the Sierra de los Organos, Upper Jurassic and Lower Cretaceous carbonates overlying the Jagua Formation are known as the Guasasa Formation, the lower part of which is the San Vicente member (Figure 3). In the original interpretation (Pszczolkowski, 1978), the Guasasa Formation comprised a thick, densely stratified lower section, deposited in very shallow waters (San Vicente member), and overlying, well-stratified rocks deposited in deeper waters (El Americano, Tumbadero, Tumbitas, and Infierno members). As implicitly recognized by Pszczolkowski (1999), the Infierno member is indistinguishable from the Pons Formation, which has priority in regional stratigraphic nomenclature.

San Vicente Member

Lithology, considerable thickness (up to 650 m [2132 ft]), and widespread geographic distribution support the interpretation of this unit at the formation level; however, local stratigraphic terminology is herein maintained. The San Vicente member includes thick-bedded to massive gray-black limestones, frequently dolomitized and with occasional chert nodules and lenses (Pszczolkowski, 1999, and references therein). No wave-resistant reef buildups have been reported. The San Vicente member has been interpreted as a carbonate shelf deposit (Hatten, 1967; Khudoley and Meyerhoff, 1971; Pszczolkowski, 1978, 1981, 1999; Myczyñski and Pszczolkowski, 1990, and references therein) accumulated on a well-oxygenated bottom, with abundant micrites containing *Favreina* (Crustacea fecal pellets) in the lower part and calcarenites (intraoosparites and intrabiosparites) in the upper part. This facies change suggests a shallowing trend of the carbonate bank (Pszczolkowski, 1981). Breccias have been observed at the base of the unit (Figure 9) (Judoley and Furrazola-Bermúdez, 1965; Hatten, 1967; Pszczolkowski, 1978; see comments on the Jagua Formation). Bedding is thinner in horizons close to the overlying El Americano member, and micrite and calcilutite beds intercalated with detrital limestones indicate initial pulses of drowning of the carbonate bank (Pszczolkowski, 1978, Cobiella-Reguera, 1996a, b) at the Kimmeridgian–Tithonian boundary. Somin and Millán (1981) reported tectonically thinned metamorphic equivalents to the San Vicente member in the Cangre belt (Piotrowska, 1978).

Fossils of stratigraphic interest are scarce in the San Vicente member (gastropods, echinoderms, and algae in Judoley et al., 1988; *Favreina salevensis* and *G. alpina* in Fernández Carmona, 1998; bivalves, algal debris, echinoid spines, and benthic forams in Pszczolkowski, 1978). The age of the San Vicente member can be interpreted with some confidence as it rests on upper Oxfordian (Bimammatum chron?) beds of the Jagua Formation. Sedimentary breccias are frequently reported from basal outcrops of the unit (e.g., Judoley and Furrazola-Bermúdez, 1965; Hatten, 1967; Myczyñski, 1976a, b; Pszczolkowski, 1999), but Knipper and Puig (1967) considered them to be of tectonic origin because of competence differences between the stratified (Pimienta member) and the massive or thick bedded (San Vicente) limestones. The abrupt Jagua-San Vicente facies change suggests a disconformity and/or unconformity, probably located at the same stratigraphic level as the Francisco-Artemisa disconformity and/or unconformity in Sierra del Rosario (Figure 3). The unit is conformably covered by lower Tithonian limestones of the El Americano member. The transition is rather abrupt, probably because of a rapid relative sea floor deepening.

On the basis of the occurrence of Hybonoticeras near the base of the overlying El Americano member (8 m [26 ft] above the top of the San Vicente member) and the biochronostratigraphic interpretation made by Myczyñski (1999), we assume that the San Vicente member did not range into the Tithonian. Nevertheless, the base could include some upper Oxfordian rocks, according to Pszczolkowski (1999, and references therein). Obviously, the age of the lowermost San Vicente beds is unresolved. This interpretation suggests that San Vicente deposition occurred during an unfavorable time for ammonites in the Guaniguanico Cordillera, both in the Sierra de los Organos (uppermost Pimienta + San Vicente member) and in the Sierra del Rosario (lower La Zarza member, as reinterpreted in this chapter). This is consistent with the close resemblance of the main stratigraphic features of the Upper Jurassic in both regions, as recognized by Pszczolkowski (1994a). No evidence of significant, widespread synsedimentary instability pointing to an abrupt morphological jump in the basin floor has been found in the transitional San Vicente-La Zarza beds in Sierra del Rosario (Pszczolkowski, 1978), neither within the San Vicente and El Americano nor within any other Kimmeridgian–Tithonian lithostratigraphic unit in western Cuba. Assuming continuous deposition within this interval, we envisage a continuous

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FIGURE 10. Well bedded (10–40 cm [4–16 in.] thick) dark limestone strata of El Americano member containing thin shaly intercalations. Rancho San Vicente, Viñales, Pinar del Rio province (Figure 2). Coordinates: 22°40′09.2″N; 83°42′33.7″W.

lateral progressive deepening from shallow-water banks (San Vicente member) to deeper neritic settings (lower La Zarza member of Artemisa Formation), with an overall carbonate ramp morphology. Meanwhile, local return to shallow-water carbonates occurred in Sierra del Rosario; the trend towards deepening continued in the Sierra de los Organos. However, lacking outcrops for transitional sections between these two ranges impedes a more integrated and conclusive interpretation.

El Americano Member

Like the San Vicente member, this unit has only been described in the Sierra de los Organos. The El Americano member consists of well-stratified gray-black limestones, with occasional fine clayey intercalations (Figures 3, 10). Maximum thickness is about 45 m (148 ft). Based on the microfacies with Saccocoma under the *Colomisphaera* sp.-*Cadosina parvula* assemblage zone (Myczyñski and Pszczolkowski, 1990) or the *Saccocoma*-Didemnidae microfacies (Myczyñski and Pszczolkowski, 1994), Pszczolkowski (1999, and references therein) interpreted these sediments as having accumulated under deep-neritic shelf conditions. This author (ibid.) interpreted microfacies with tintinnoids (Myczyñski and Pszczolkowski, 1990) and especially with radiolaria (Myczyñski and Pszczolkowski, 1994) as evidence for outer shelf or even bathyal environments at the end of the Tithonian. However, Myczyñski (1989) interpreted shallowing during the late Tithonian. As usual, it is unclear whether the evolution of microfacies was mainly controlled by depth or, instead, by combined factors such as distance from shore, hydrodynamics, and ecological conditions. This latter combination of factors is difficult to reconstruct with certainty in paleomargins undergoing deformation near oceanic accretion zones, as was the North American paleomargin in western Cuba during the Tithonian and Early Cretaceous (e.g., Marton and Buffler, 1999).

Ammonites from the El Americano member have long been known. Myczyñski and Pszczolkowski (1990, 1994) and Myczyñski (1999, and references therein) reported successive assemblages of ammonites and/or calpionellids. In recent studies, ammonite assemblages are characterized by *Mazapilites* with or without *Hybonoticeras*, *Pseudolissoceras* commonly associated with the so-called "*Virgatosphinctes*", *Paralytohoplites* (previously *Lytohoplites*), and the *Proniceras-Durangites-Kossmatia-Corongoceras* and *Protancyloceras-Vinalesites*; the latter two assemblages were recently replaced by the *Durangites-Himalayites-Salinites* assemblage. Pszczolkowski (1999) concluded that the El Americano member was Tithonian in age. Nevertheless, no conclusive interpretation of the upper Tithonian based on ammonites in Mesoamerica exists, as remarked by Villaseñor et al. (2000) for Mexico, and an updated analysis of combined ammonite and calpionellid ranges is required. Recently, Pszczolkowski and Myczyñski (2003) interpreted the topmost horizons of the El Americano member to be early Berriasian in age, and Pszczolkowski et al. (2005) placed the Jurassic/Cretaceous (J/C) boundary in the youngest beds of the El Americano member based on the combined record of calpionellids, radiolaria, nannoconids, and ammonites. Yet calpionellids and/or ammonites in Tavera et al. (1994) and Olóriz et al. (1995) allow upper horizons from the El Americano member previously considered as part of the Crassicollaria and the Calpionella zones to be reinterpreted as early to middle Berriasian (e.g., Pop, 1976; Judoley et al., 1988; Myczyñski, 1989; Myczyñski and Pszczolkowski, 1990; see table 5 of Pszczolkowski, 1978). Significantly, calpionellids reported from horizons within the upper El Americano member and interpreted as belonging to the upper Crassicollaria and/or Calpionella zones (Pop, 1976; Judoley et al., 1988; Myczyñski, 1989; Myczyñski and Pszczolkowski, 1990; see table 5 of Pszczolkowski, 1978) indicate early to early–middle Berriasian.

Tumbadero Member

The Tumbadero member includes well-stratified, commonly laminated mudstones and wackestones (Figure 3). Abundant calpionellids and radiolarians are observed; the latter typically associated with intercalations of black, cherty horizons. Thickness is up to 50 m (164 ft). Based on progressive deepening interpreted for the underlying El Americano member proposed by Pszczolkowski (1999), sediments of the Tumbadero member have been assumed to indicate accumulation in bathyal waters, below the aragonite compensation depth. Pszczolkowski et al. (2005) proposed generalized

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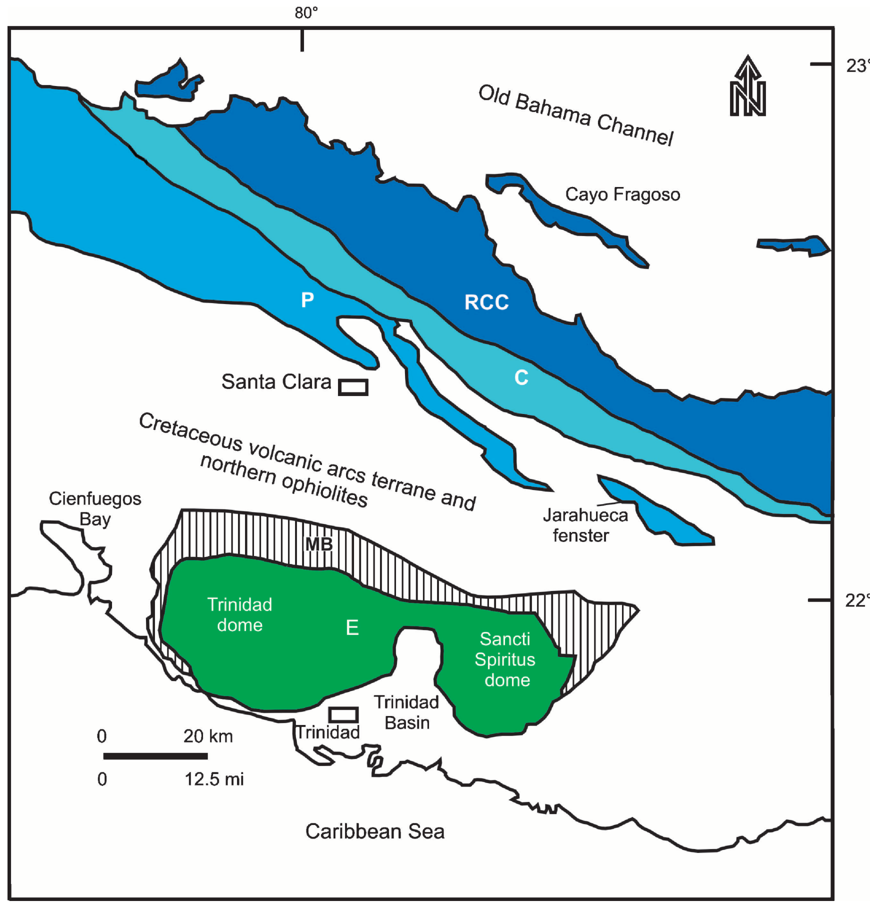

FIGURE 11. Main Upper Jurassic–Neocomian paleotectonic units in central Cuba. RCC = Remedios-Cayo Coco-Canal Viejo zone (interpreted as the southern fringe of the Bahamas platform); C = Camajuaní zone; P = Placetas zone; MB = Mabujina complex (metamorphic basement of the volcanic terrane); E = Escambray massif. Contacts between all these units are tectonic, resting ophiolites and the volcanic terrane on passive continental margin sequences.

poor oxygenation for deep waters in the proto-Caribbean Basin at the time. As in the case of the El Americano member, the criteria employed to reconstruct paleodepth are not conclusive, although Tumbadero member deposits undoubtedly accumulated offshore.

Ammonites from the Tumbadero member are scarce and difficult to identify (e.g., Myczyñski and Pszczolkowski, 1990; Myczyñski, 1994), making calpionellid data of special value. Following Tavera et al. (1994) and Olóriz et al. (1995), the age of the Tumbadero member is early to middle or early–late Berriasian (Figure 3) in view of data obtained by (1) Pop (1976) from cherty horizons in his Artemisa Formation in the Sierra de los Organos; (2) Pszczolkowski (1978, table 5), who indicated the dominance of *Calpionella* spp. and reported *Calpionellopsis* spp. from the uppermost 10 m (33 ft) in this member; and (3) Myczyñski (1989) and Myczyñski and Pszczolkowski (1990). Pszczolkowski (1978, 1999) assumed a Berriasian age for the Tumbadero member, which Pszczolkowski and Myczyñski (2003) estimated at most from earliest to early–late Berriasian. Recently, Pszczolkowski et al. (2005) interpreted lower Tumbadero deposits to be *C. alpina* subchron in age. The lower cherty levels of the Tumbadero member must correlate with the Sumidero member of the Artemisa Formation.

Tumbitas Member

According to Pszczolkowski (1999), the Tumbitas member contains thick bedded light gray biomicrites with a rich pelagic fossil association (calpionellids, radiolarian, and nannoconids). The thickness is around 40 m (131 ft) but in some sections attains 80 m (262 ft). The unit is upper Berriasian–lower Valanginian, according to calpionellids in Pszczolkowski (1978, 1999).

Upper Jurassic in the North American Paleomargin in North-Central Cuba

The second large outcrop of the North American Mesozoic paleomargin in Cuba is located along its northern fringe, from northeastern Havana province, in the west, to Holguin, in the east (Figures 1, 11). As in western Cuba, alpine tectonic style is recognizable (Figure 12); but in contrast to western Cuba, where extensive Jurassic outcrops are seen, in north-central Cuba, these are limited and Cretaceous rocks predominate. The overwhelming majority of outcropping Jurassic rocks belong to the uppermost Jurassic because of detachments coincident with this stratigraphic level. Although numerous wells exist, relatively few data have been published.

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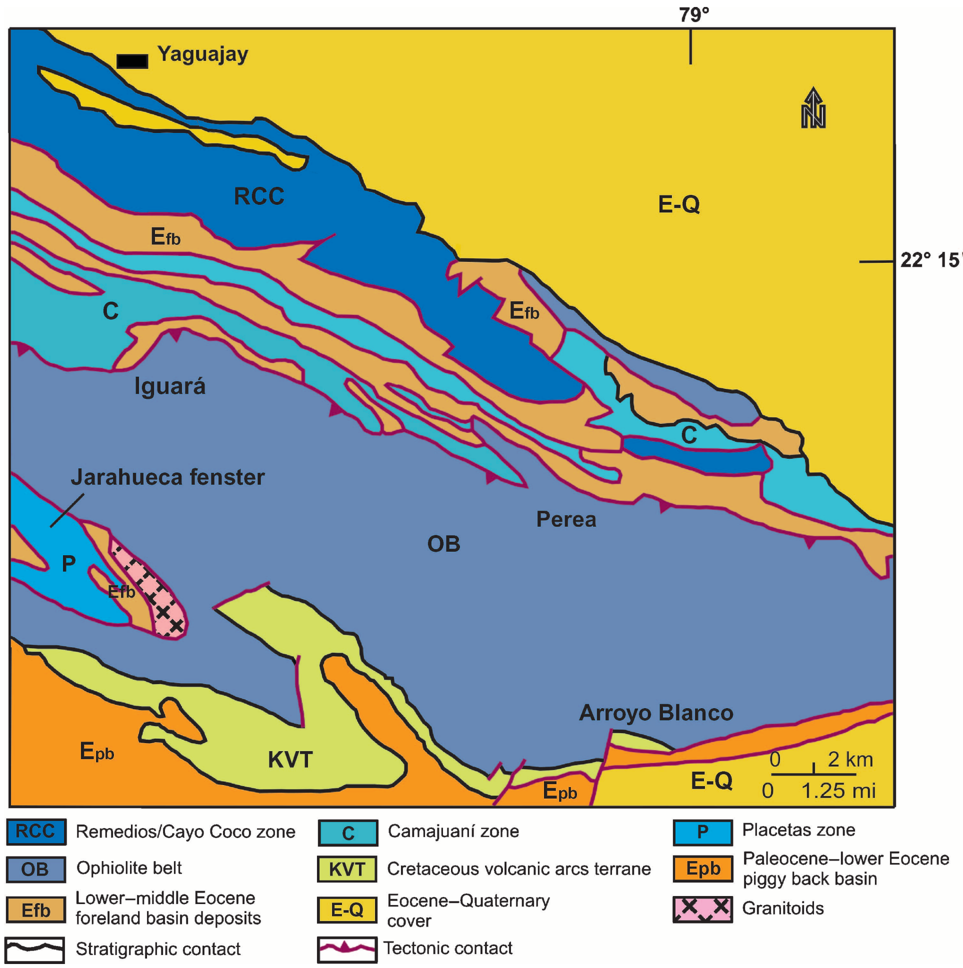

FIGURE 12. Tectonic map of northern Sancti Spiritus province (data from Pushcharovsky, 1988, and other sources). The map shows the well-developed northwest–southeast trend of the continental paleomargin zones. See Figure 1 for the location.

The quality and precision of these data, generally poorer than for western Cuba, impede precise correlation between the two regions.

From north to south, and slightly modifying the nomenclature preferred by Cuban specialists (see below), three stratigraphic successions may be distinguished in the north-central Cuba late Jurassic–Berriasian paleomargin: (1) The Remedios-Cayo Coco-Canal Viejo, (2) the Camajuaní, and (3) the Placetas zones (Figures 11, 13). This stratigraphic scheme follows guidelines established by field and oil geologists over more than 50 years and is supported by new data obtained from intensive oil and gas exploration conducted during the last 40 years (e.g., Meyerhoff and Hatten, 1968; Pardo, 1975; Kuznetsov et al., 1985; Díaz Otero et al., 1992, 1997; Alvarez-Castro et al., 1998; Blanco González, 1998; Segura-Soto and Blanco-Bustamante, 1998; Pszczolkowski and Myczyñski, 2003). Structural and stratigraphic interpretations envisage increasing relative autochthony northward across these structural zones (e.g., Pindell et al., 2006). Detailed stratigraphic research on the Camajuaní and Placetas zones clearly shows their original spatial relationships with the Florida-Bahamas megabank (e.g., Cobiella-Reguera, 2000; Pszczolkowski and Myczyñski, 2003; Pindell et al., 2006).

Remedios-Cayo Coco-Canal Viejo Zone

This zone corresponds to the southern boundary of the Bahamas platform (Figures 11, 12) (Díaz Otero et al., 1997). Data on the Jurassic successions are obtained almost exclusively from subsurface geology. The Jurassic section is divided into two large successions (Figure 13). The lower, the Punta Alegre Formation (Meyerhoff and Hatten, 1968), is found in three large diapirs and some wells. Punta Alegre Formation is made up of evaporites (anhydrites, gypsum and halites) with rare shales. Because of diapirism, exotic blocks of limestones and dolomites of variable size lie among the evaporites. The unit seems to lie beneath the upper Jurassic–lower Cretaceous Cayo Coco Formation. Salvador (1987) remarked on the possible correlation of the Punta Alegre Formation with Callovian evaporites from the rim of the Gulf of Mexico, an opinion shared by Alvarez Castro et al. (1998). In both cases, the age is assumed almost exclusively on the basis of the stratigraphic position, using poor biostratigraphic

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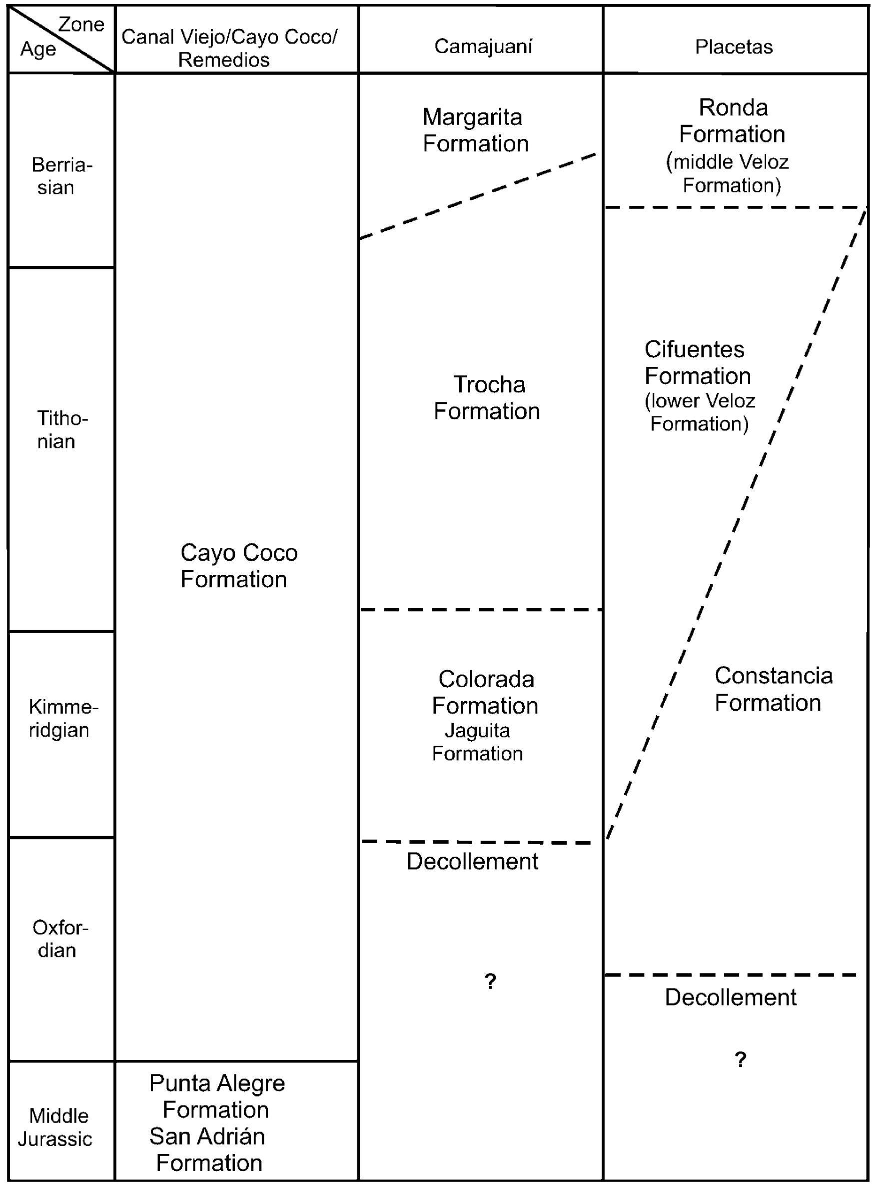

FIGURE 13. Schematic correlation chart of Upper Jurassic–Neocomian deposits in the north-central Cuban Mesozoic paleomargin.

data. Southwest of the city of Matanzas (100 km [62 mi] east of Havana), salt deposits (gypsum) in small tectonic sheets (Figure 14, San Adrián Formation) could correlate with the Punta Alegre Formation, although these deposits contain more xenoliths and clayey intercalations (Meyerhoff and Hatten, 1968; Albear-Fránquiz and Piotrowski, 1984).

The upper succession is represented by the Cayo Coco Formation (Figure 13), comprising about 1800 m (5905 ft) of carbonates (limestones and dolomites) and anhydrites. No anhydrites are present in southernmost sections (Perros Formation in some stratigraphic schemes). The presence of evaporites in this unit and in the underlying Punta Alegre Formation suggests sedimentary continuity, but available biostratigraphy does not allow for greater precision. Both the Punta Alegre Formation and the San Adrián Formation are shallow-to-very-shallow sediments (continental to inner shelf transitional environments). The Cayo Coco Formation was interpreted as deposited on a shallow submarine plateau, near the Bahamas-Florida block. (e.g., Meyerhoff and Hatten, 1968; Schlager et al., 1984), and at the edge of the Bahamas platform (Pindell et al., 2006).

In the Remedios-Cayo Coco-Canal Viejo zone, subsurface data are insufficient for a precise identification of horizons belonging to the upper Jurassic in the evaporitic sediments of the Punta Alegre Formation (if indeed such horizons exist). In the context of the regional interpretation favored in this study, we envisage a possible correlation with evaporites of the Gulf of Mexico Basin (see above), meaning that the carbonates of the Cayo Coco Formation may have initiated late Jurassic

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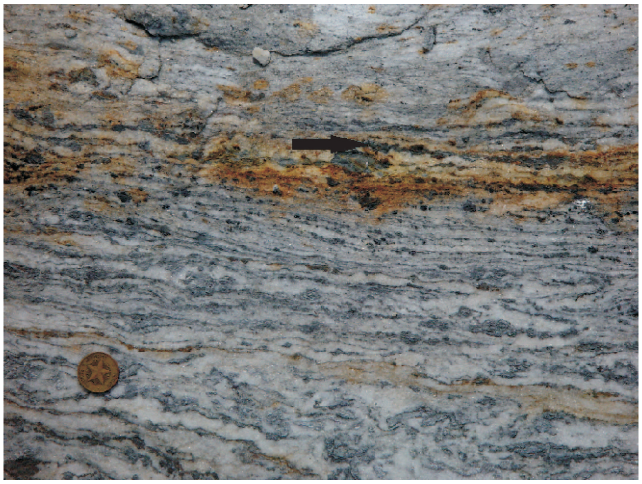

Figure 14. Severely deformed rocks in San Adrián diapir (see Figure 1). Folded recrystallized gypsum locally contains horizons with abundant distorted shaly clasts (arrow). According to Albear-Fránquiz and Piotrowski, 1984, these clasts probably were interbeds originally. Coordinates: 23°04′45.0″N; 81°41′22.5″N.

deposition (Figure 11). Nevertheless, microfossils identified to date do not allow for the involvement of Cayo Coco Formation carbonates in the correlations here considered.

Camajuaní Zone

Upper Jurassic and Berriasian deposits are better represented on the surface than the Remedios-Cayo Coco-Canal Viejo zone (Figure 11). The Camajuaní zone mainly comprises carbonate sediments, frequently dolomitized, showing intercalations with clastic textures, including breccias (Figure 13) (e.g., Meyerhoff and Hatten, 1968; Shopov, 1982) and abundant biogenic-pelagic limestones. Terrigenous sediments are scarce. Cherty horizons appear within the Berriasian. The oldest layers in the Camajuaní zone date from the Kimmeridgian, and their basal contact is a tectonic one (Figure 13). According to Cuban oil geologists, the Kimmeridgian and the Tithonian are represented by the Jagüita and Colorada formations (Alvarez Castro et al., 1998; Sánchez et al., 1998; Segura-Soto and Blanco-Bustamante, 1998), which are composed of grayish to brownish micritic, pelagic limestones (*Saccocoma*, ammonite embryos, Cadosinidae, and radiolaria) alternating with detrital limestones (finer-grained in the Jagüita Formation) that commonly show graded bedding. In the Colorada Formation, clastic limestones contain abundant oolites and common minor irregularities at the base of the strata related to erosion of the underlying sediments (turbidites?). Intercalations of shales and siltstones exist. Pszczolkowski and Myczyñski (2003) considered the Tithonian and, locally, most of the Berriasian beds to constitute an independent unit, the Trocha Formation (Figure 13). The Berriasian is represented by the Margarita Formation, in which Hatten et al. (1988) reported microbioclastic, oolitic limestones with nannoconids intercalated in mudstones and wackestones with calpionellids and radiolaria. Segura-Soto and Blanco-Bustamante (1998) hold the clastic limestones to be turbiditic deposits and believe that the Camajuaní zone represents sedimentation at the base of the slope corresponding to banks of the Remedios-Cayo Coco-Canal Viejo zone. Schlager et al. (1984) considered the Camajuaní zone to continue westward in the eastern Gulf of Mexico. Pindell et al. (2006) interpreted Camajuaní successions to represent the southern Bahamas continental slope and rise (Khudoley and Meyerhoff, 1971; Meyerhoff and Hatten, 1974; Pardo, 1975, among others). In this context, the Camajuaní zone could correspond to slope deposits accumulated immediately south and southwest of the Bahamas-Florida megabank during the late Jurassic and early Cretaceous (a subject which will be revisited below) on relatively stable grounds because no signs of synsedimentary instability, typical in slope deposits, have been identified. In fact, outer-shelf deposition could also be envisaged for Camajuani zone deposits during the Jurassic and the early Cretaceous.

The following fossils have been identified from the Colorada Formation: *Dingodinium tuberosum*, *Crustocadosina semiradiata*, *Commitosphaera pulla*, *Guttilina* sp., *Favreina* sp., *Saccocoma* sp., *Perisphinctaceae* sp. and *Pseudolissoceras* sp., which Sánchez et al. (1998) interpreted as Kimmeridgian–Tithonian in age (at least the early Tithonian is present with *Pseudolissoceras*). In the Margarita Formation, Hatten et al. (1958) found *C. elliptica*, *C. carpathica* (=*T. carpathica*), *C. oblonga* (=*Calpionellopsis oblonga*) and *C. darderi* (=*Calpionellites darderi*), indicating the middle Berriasian to upper Valanginian (Figure 13). Cherty sediments in the Margarita Formation, Camajuaní zone, date at least from the middle Berriasian according to calpionellids.

Placetas Zone

The Placetas zone is the southernmost recognizable belt of the Jurassic North American paleomargin in central Cuba (Figure 11). Grenvillian metamorphic rocks form a basement intruded by Jurassic (172 Ma old) granites (Somin and Millán, 1981; Renne et al. 1989). Two main lithologic successions can be distinguished in most of the area. The lower one is mainly terrigenous, and the upper one is almost entirely made up of carbonates (Alvarez Castro et al., 1998; Pszczolkowski and Myczyñski, 2003, and references therein) (Figure 11). Pardo (1975) and Pszczolkowski (1986b) considered the

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terrigenous section to rest on granites with basal arkoses of granitic clasts derived from its substrate (? regolith). Above, and nearly always through tectonic contact, lie more varied arkosic sediments (Constancia Formation) showing a gradual transition to the overlying carbonates (Figure 13) (Somin and Millán, 1981; Renne et al., 1989; Pszczolkowski and Myczyñski, 2003).

Until recently, the age of the basal terrigenous succession of the Placetas zone was estimated to be Tithonian or Berriasian because the overlying limestones were considered to belong to the Berriasian. Pszczolkowski (1986b) reported *C. elliptica* (Cadisch), *C. alpina* (Lorenz), *Tintinopsella carpathica* (*Murgeanu et Filipescu*), and *Remaniella dadayi* (*Knaue*) in limestone intercalations of the upper Constancia Formation. However, oil wells in the north of the province of Matanzas show limestone intercalations in the upper part of the basal terrigenous succession (also identified as the Constancia Formation), which yielded *Globuligerina oxfordiana*, *Globuligerina* spp., *Lenticulina* sp., *Orbiculiforma* sp., and *Cenosphaera* sp. (Díaz-Colell, 1996; Alvarez Castro et al., 1998; Blanco González, 1998). Blanco González (1998) also recorded spores and concluded that the Constancia Formation (as defined by Cuban oil geologists) is Oxfordian–early Kimmeridgian in age (cf. Alvarez Castro et al., 1998). The recent observation of *Globuligerina oxfordiana* in the Constancia Formation can be considered indicative of the Oxfordian, although detailed paleontological analyses are necessary to obtain a more precise biochronostratigraphy (see Grigelis and Gorbatchik, 1980; Banner, 1982; Bignot and Janin, 1984; Giovanelli and Schiavinotto, 1986; Samson et al., 1992, for extended treatment of Jurassic Conoglobigerinidae and Globuligerinidae). Current data for foraminifers and spores seem to suggest that the changeover of siliciclastic sedimentation (Constancia Formation) to carbonates (named Cifuentes Formation by Cuban oil geologists) probably occurred during the latest Oxfordian or earliest Kimmeridgian (Figure 13), but precise data are not available. Recently, Pszczolkowski and Myczyñski (2003) revisited sections from the lower Placetas zone and interpret the Constancia (terrigenous sequence)-Veloz-Cifuentes (carbonate sequence) Formation to be time transgressive (diachronous), migrating from Kimmeridgian? to upper Berriasian as one moves from west (northern Matanzas) to east (northern central Cuba) (Figure 13). According to the preceding data, age interpretations of carbonate intercalations in the upper Constancia Formation cannot be considered conclusive.

Pszczolkowski and Myczyñski (2003) concluded that the Constancia Formation strata were probably deposited in grabens, in a tectonic setting similar to the pre-Cretaceous siliciclastic sections of the southeastern Gulf of Mexico grabens shown by Marton and Buffler (1994, 1999).

The Constancia Formation resembles the Bacunayagua Formation, which is found as slivers between tectonic sheets of the Placetas sequence. The Constancia Formation is found in deep wells (sometimes called the A horizon) of northern Havana and Matanzas provinces. The Bacunayagua Formation also occurs in rare and small outcrops. The arkosic sandstones and conglomerates of the Bacunayagua Formation have been considered Campanian–Maastrichtian and even early Tertiary in age (Albear-Fránquiz and Iturralde-Vinent, 1985), but the mineral composition, which is rich in clasts of sialic provenance, is very different from the Upper Cretaceous or early Paleogene volcaniclastic sandstones of Cuban oil fields.

According to Alvarez Castro et al. (1998), Blanco González (1998), and Sánchez et al. (1998), the overlying Kimmeridgian–Tithonian Cifuentes Formation is composed of dark gray to black, well-stratified biomicrites and mudstones with fine terrigenous intercalations (Fernández Carmona, 1998). Kimmeridgian deposits in this formation, with *Favreina salevensis*, *Didemnoides moreti*, and algae, accumulated in very shallow waters, whereas the Tithonian ones did so in outer shelf or even bathyal conditions (Fernández Carmona, 1998). The lower part of the Cifuentes Formation (lowermost Veloz Formation according to Pszczolkowski and Myczyñski, 2003) contains *Globochaete alpina* and *Didemnoides moreti*, whereas *Favreina salevensis*, *Globochaete alpina*, *Saccocoma*, *Chitinoidella* spp, *Cadosinidae*, and aptychi have been found in the middle and upper parts. *Crassicollaria* spp. and *Calpionella alpina* (large forms), of Tithonian age, appear in the uppermost layers of the lower Cifuentes Formation. Therefore, shallow carbonate sedimentation during the Kimmeridgian was followed by open-marine sedimentation during the Tithonian. This trend is similar to that identified in coeval deposits in the Guaniguanico Mountains.

Biomicrites with radiolaria and cherty and dolomitic intercalations of the Ronda Formation (middle part of Veloz Formation) (Pszczolkowski and Myczyñski, 2003) overlie the Cifuentes Formation (Fernández Carmona, 1998; Sánchez et al., 1998). Pop (1976) interpreted lower Ronda Formation beds as being of late Berriasian to probable Valanginian age. Calpionellid assemblages identified by Pop (1976) in deposits with cherty intercalations in the former province of Las Villas and the lithostratigraphic scheme allow us to deduce that Ronda Formation deposition may have begun during the middle to late Berriasian (Figure 13).

Further east, in northern Camaguey province, the Constancia Formation has not been identified. Beneath the carbonate sections, reported as the Veloz Formation (Iturralde-Vinent, 1988a, b), pillow basalts, brecciated hyaloclastites with fine intercalations of micritic and biomicritic limestones with radiolaria, calpionellids, *Saccocoma*, *Cadosina* sp., and ammonite embryos have been found. At the base of the Veloz Formation, Iturralde-Vinent (1988a, b) reported remains of *Saccocoma*, *Cadosina*

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sp., *Chitinoidella cubensis*, and ammonites. These data are interpreted as Tithonian. We cannot exclude, however, the possibility of older upper Jurassic horizons (e.g., Kimmeridgian, at least in part) for tholeitic rocks of the Nueva Maria Formation if *Saccocoma* sp. and *Cadosina* sp. come from levels below those in which calpionellids were found. Pszczolkowski and Myczyñski (2003) assumed an early Tithonian age for the Nueva Maria Formation, whereas the Veloz Formation would span from upper lower Tithonian to lower Cretaceous in northern Camaguey. Iturralde-Vinent (1997) envisaged the Nueva Maria Formation as part of the proto-Caribbean oceanic crust, but data supporting this inference are insufficient.

From the preceding comments, several general features of the upper Jurassic–Cretaceous stratigraphy of the Sierra del Rosario and Placetas zone are obviously very similar and possibly belong to the same hemipelagic tectonopaleogeographic domain, as envisaged by Cobiella-Reguera (2000) and recently proposed by Pszczolkowski and Myczyñski (2003). The latter authors used ammonite paleobiogeography to reinforce close relationships during Tithonian to early Cretaceous among the Guaniguanico sections, and the central Cuba Placetas and Camajuani zones. In between Guaniguanico and central Cuba, upper Jurassic–lower Cretaceous Placetas zone sections (and less frequently, beds from the Camajuani zone) have been recorded in many deep wells in northern Havana and Matanzas provinces (Kuznetsov et al., 1985). These units also crop out occasionally in northern Matanzas (Veloz Formation in Pushcharovsky, 1988) and northern Havana (Albear-Fránquiz and Piotrowski, 1984). However, greater bio- and lithostratigraphic precision is required to establish a reliable correlation between upper Jurassic–lower Cretaceous sections of the Guaniguanico Cordillera and north-central Cuba.

Other proposals for correlating Placetas and Guaniguanico deposits have been made. Schlager et al. (1984) envisaged regional correlation for the Placetas deposits and considered leg 77 sites 537 and 538 to represent the western prolongation of the Placetas zone. However, lower Cretaceous carbonate pelagic deposits drilled in both sites were on isolated knolls, whereas Placetas-type pelagic and hemipelagic sediments accumulated in deeper waters southward from the Bahamas platform. In fact, deep-water Mesozoic deposits of the southeastern Gulf of Mexico (Schlager et al., 1984) are very similar to Placetas-Sierra del Rosario sections. The most significant difference is the occurrence of terrigenous sediments in some Cuban sections, particularly in western Cuba, and their virtual absence in the southeastern Gulf. In addition, Schafhauser et al. (2003) reported Berriasian and Aptian deep-water carbonate deposits in Belize at the southern extension of the Guaniguanico Basin. These beds would have been thrusted from the east on to Cretaceous neritic carbonate sections (Coban Formation) and lower Tertiary turbidites (Sepur Formation), probably during the early Tertiary. If this interpretation is correct, an earliest Cretaceous deep-water basin extended along the southern fringe of the North American plate from Camaguey (east-central Cuba) to the present northwestern Caribbean, east from Belize (i.e., the proto-Caribbean or westernmost extreme of the Tethys). North of the deep-water seaway, extensive carbonate banks developed on the Bahamas-Florida platform and surrounding the emergent Yucatan Platform.

Upper Jurassic–Lowermost Cretaceous in the North American Paleomargin in Eastern Cuba (Maisí)

In easternmost Cuba, a small area in the Maisí region (Figure 1) shows metasedimentary upper Jurassic and Cretaceous rocks attributed to a continental margin (Cobiella-Reguera, 1983, 2000; Iturralde-Vinent, 1996a). Contacts are tectonic, except with the overlying upper Tertiary sedimentary deposits, which most probably are erosional across the region. Iturralde-Vinent (1996a) considered these rocks to belong to the Asunción terrane, but their tectonic setting below the ophiolite belt favors their interpretation as part of the paleomargin (Cobiella-Reguera, 2000, 2005a).

Phyllites and dark-colored shales, with quartzitic metasandstones, marbles, and metabasalts, are found in the lowest structural unit (Sierra Verde Formation). Millán et al. (1985) reported poorly preserved calpionellids and *Nannoconus* (*sensu lato*) that suggest a Tithonian to earliest Cretaceous age for a sample gathered from an isolated outcrop of unclear stratigraphic-structural setting (G. Millán, 1985, personal communication). Overlying the lower structural unit are black marbles, occasionally dolomitic, and calcareous and calcareous-micaceous schists, containing episodic intercalations of metamorphic cherts (La Asunción Formation) (Cobiella-Reguera, 1983). According to Millán et al. (1985), *Ophthalmidium* sp., *Spirillina* sp., *Chitinoidella* sp. and *Miliolidae* were identified in some horizons. The presence of *Chitinoidella* in the sample suggests an age ranging from late–early Tithonian to early–late Tithonian. Cobiella-Reguera (1983) and Cobiella et al. (1984) describe the striking resemblance between the Sierra Verde Formation and Jurassic terrigenous successions cropping out in western Cuba (metavolcanics included), but Millán et al. (1985) attributed a Cretaceous age to the Sierra Verde Formation. The metacarbonates (Chafarina or La Asunción Formation) are Tithonian in age, at least in part. Structural complexity and the poor information available do not allow the correlation of Maisí outcrops with those of the North American paleomargin in western and central Cuba.

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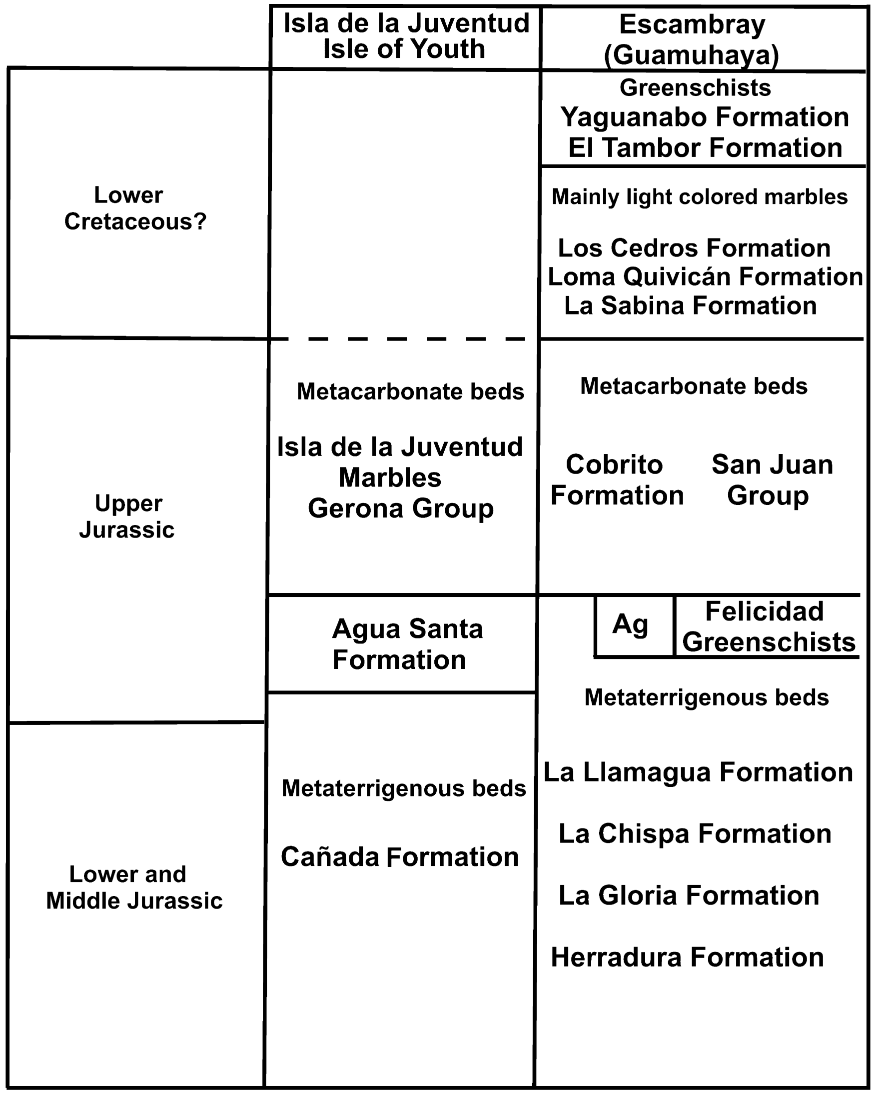

Figure 15. Correlation chart of the southern metamorphic terranes (data from Millán Trujillo, 1997a, b, c, and references therein). Ag = Algarrobo schists.

Passive Paleomargin Sequences in the Metamorphic Massifs of Southern Cuba (Isla de la Juventud and Escambray)

Metamorphic rocks belonging to passive continental margin sequences crop out in two large areas of southern Cuba: the metamorphic massifs of Isla de la Juventud and the Escambray (Guamuhaya). Both regions are extensive tectonic windows beneath large nappes formed by Cretaceous volcanic materials and their metamorphic basement (Figures 1, 11). Since 1970, southern Cuban metamorphic sections have been studied in some detail (e.g., Somin and Millán, 1981; Millán et al., 1985; Millán Trujillo, 1997a, b, c; Stanek et al., 2006). In both these massifs, the succession attributed to the Jurassic represents deposition on a passive paleomargin, with a lower metaterrigenous sequence, followed by metacarbonates (Millán Trujillo, 1997a) (Figure 15). However, great tectonic complexity affecting Jurassic rocks (tectonic sheets) and deformation caused by metamorphism make stratigraphic interpretation difficult (Stanek et al., 2006).

In Isla de la Juventud (Isle of Youth or Pinos; Figures 1, 15), the lower metaterrigenous, quartzose succession (Cañada Formation) shows abundant intercalations of micaceous and graphitic schists and provided psilate trilete spores that suggest a Mesozoic age (Millán Trujillo, 1997a). A transitional upper section of schists with marble intercalations has been identified (Agua Santa Formation). The upper part of the geologic section is made up of marbles (sometimes dolomitic) of the Gerona Group. In the lower part of the last unit, benthic foraminifers (*Spirillina* sp., *Ophthalmidium* [*Spirophthalmidium*] sp.) of Mesozoic age (middle Triassic–late Jurassic) have been found, together with unidentified cephalopods (Millán Trujillo 1997a). Overlying them are thick marbles barren in fossils, and layers of metacherts (Isla de la Juventud marbles). Although biostratigraphy is relatively imprecise, the similarity of the major lithologic features to those identified in the Guaniguanico Cordillera has led

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almost all researchers to accept a correlation between these two domains (Millán Trujillo, 1997a, b).

As in the Isla de la Juventud, the oldest beds in the Escambray (Guamuhaya) Massif (Figures 1, 15) are quartzose, metaterrigenous beds, showing locally variable metamorphism (La Chispa, La Llamagua, La Gloria, and Herradura formations in Millán Trujillo, 1997c). Transitional sections between the metaterrigenous and the upper metacarbonates (upper La Chispa Formation, Figure 15) also contain local mafic metavolcanic rocks (Felicidad Greenschists). In the lower part of the metacarbonate successions (San Juan Group), poorly preserved ammonoid remains of late Oxfordian age (*Perisphinctes* and *Mirosphinctes*) have been found (Millán and Myczyñski, 1978, 1979, who interpreted middle Oxfordian). These authors also described a single, ex-situ specimen as Perisphinctidae, probably of Tithonian age. At the middle-upper part of this unit (Mayarí Formation), Millán Trujillo (1997a) reported remains of Perisphinctidae showing morphology comparable to that of Tithonian forms, in addition to *Cadosina* sp. and forms similar to *C. carpathica* (Borza) (Millán Trujillo, 1997a, c). The latter species is interpreted as Kimmeridgian–Tithonian by Fernández Carmona and Pendás Amador (1998). Above the black marbles section, unfossiliferous pale metacarbonates were tentatively interpreted by Millán Trujillo (1997a) as Cretaceous.

Iturralde-Vinent (1996a, 2006) joined the Mesozoic sections of Escambray, Isla de la Juventud, and Guaniguanico mountains in his Southwestern terranes. Indeed, Jurassic sections in the Guaniguanico and Escambray mountains are similar. According to Cobiella-Reguera (1996a), they were probably deposited in the same basin, although their present respective location with regard to ophiolites and the Cretaceous volcanic arcs terrane is different. Regional geology suggests that rocks in Escambray and Isla de la Juventud were always located south of the Cretaceous volcanic arcs, whereas upper Jurassic–Cretaceous sections belonging to the Guaniguanico Cordillera were deposited along the North American margin (Cobiella-Reguera 1996a). Data from the southeastern Gulf of Mexico by Marton and Buffler (1999) and Moretti et al. (2003), and also from northern central Cuba (Cobiella-Reguera, 2000; Pszczolkowski and Myczyñski 2003), clearly show close stratigraphic relationships with Mesozoic sedimentary sections in Guaniguanico. Therefore, it seems unlikely that the latter are tectonostratigraphic terranes (e.g., as envisaged by Iturralde-Vinent, 1996a, 2003, 2006; Pszczolkowski, 1999; and partially Pindell et al., 2006) because they do not represent blocks exotic to the North American Mesozoic margin.

Pindell et al. (2006) described the Escambray terrane as a "…tectonically-unroofed, deep level of the Great Arc's forearc where passive margin strata has been subducted and subcreted in the Aptian-Albian… p. 323" The Escambray-Cretaceous volcanic arc terrane (represented by the Mabujina complex) tectonic contact is crossed by 88–80 Ma pegmatites (Stanek et al., 2006), showing that terrane welding in central Cuba is probably a pre-Coniacian event. According to Pindell et al. (2006), the southern metamorphic terranes and Guaniguanico were torn from the eastern or southern Yucatan margin during the Campanian and Maastrichtian, when the western-leading edge of the Great Caribbean Arc slid along the Yucatan border. In that case, at least some remains of Jurassic passive margin sections recording a middle Cretaceous high-pressure metamorphic event or structures pointing to pre-Coniacian thrusting should be present in the eastern Yucatan margin. However, no evidence for such events in southeastern Yucatan is reported in the geological literature (e.g., Morán-Zenteno, 1994). Other authors have evoked a Yucatan (Maya block) origin for the southern metamorphic terranes and Guaniguanico (Iturralde-Vinent, 1996a; Kerr et al., 1999; Schaffhauser et al., 2003). However, no sign of such an extraordinary event (i.e., terrane emplacement) has been reported, and the correlation between the Cuban sections (Guaniguanico Cordillera, Isla de la Juventud and Escambray Massif) and southeastern Yucatan has only been attempted to date by the latter authors. According to Schaffhauser et al. (2003), the lower Cretaceous Guaniguanico-like sections in western Belize were emplaced as thrust sheets between the Maastrichtian and the Eocene, several million years after the Pindell et al. (2006) proposed strike slip and collision of the Great Caribbean Arc with southeastern Yucatan. In the authors' opinion, no solid tectonic or stratigraphic evidence pointing to an original position for Cuba's southern metamorphic terranes along the Yucatan southeastern margin exists; this is compatible with the interpretation of Escambray as a Mesozoic polygenetic unit (terrane) amalgamated into a subduction zone (e.g., Cobiella-Reguera, 2000; Garcia-Casco et al., 2006; Stanek et al., 2006).

Final Remarks on Paleogeography and Tectonic Evolution. General Correlation with Late Jurassic–Berriasian Events in the Southeastern Gulf of Mexico

Advances in the knowledge of the regional geology during the last 30 years in Cuba and its surroundings, especially the southeastern Gulf of Mexico, allow a regional correlation of the upper Jurassic–Berriasian sequences and events. The passive margin type sections in the Guaniguanico mountains, north-central Cuba, Maisí (easternmost Cuba), and the southern metamorphic massifs record part of the early stages of the breakup of Pangea in Mesoamerica and the birth and early development of the southeastern Gulf of Mexico and the westernmost Tethys (proto-Caribbean).

According to Marton and Buffler (1999) (see also Salvador, 1987; Pindell, 1994, among others), the oldest oceanic crust in the Gulf of Mexico is probably of Callovian age and was formed in the central part of the basin. Later, in the Oxfordian, the process extended to the present eastern Gulf of Mexico, moving south until the Berriasian. The process was characterized by extensive rifting in the southeastern Gulf, which was deformed as grabens and semigrabens separated by uplifted blocks (Marton and Buffler, 1999; Moretti et al., 2003). Some intrusive mafic magmatism accompanied this movement (Marton and Buffler, 1994, 1999; Schlager, Buffler et al., 1984). This tectonic setting was related to the drifting and rotation of the Yucatan (Maya) block, which attained its present position in the Berriasian (Marton and Buffler, 1994, 1999).

Marked changes in paleogeography in western Cuba during the latest-middle to late Jurassic (especially the Oxfordian) were involved in the establishment of a deep seaway between the proto-Gulf of Mexico and the central North Atlantic. These events favored the entrance of middle–late Oxfordian ammonites into the basin where Sierra de los Organos and Sierra del Rosario (Guaniguanico Cordillera) sediments accumulated. Magmatism recorded in the El Sábalo Formation and in small isolated diabase bodies in the upper Artemisa Formation (Sumidero member) is possibly related to this process (Cobiella-Reguera, 1996a).

A clear correlation of the total stratigraphic range extending from horizons with carbonate concretions in the upper San Cayetano Formation to the top of the Jagua Formation in western Cuba is observed, with the initial third-order tectonoeustatic sequence (3rd-TES-I) recognized at the northern rim of the Gulf of Mexico Basin and north-central Mexico (Olóriz et al., 2003).

Marton and Buffler (1994, 1999) (see also Schlager, Buffler et al., 1984; Moretti et al., 2003) divided the supposed upper Jurassic sections in the southeastern Gulf in two main sequences: (1) a lower terrigenous one and (2) upper marine carbonates. This is the same general trend as the upper Jurassic–Berriasian North American paleomargin deposits in Cuba (Cobiella-Reguera, 2000; Pszczolkowski and Myczyñski, 2003). The transition from terrigenous to carbonate sedimentation occurred in the late middle Oxfordian in western Cuba (and possibly in the Escambray mountains of central Cuba, Figure 15). Possibly, the event was related to the opening process of a narrow oceanic depression in the southeastern Gulf and the origin of the oceanic proto-Caribbean (westernmost Tethys) Basin. In the central Cuba Placetas zone, the terrigenous-carbonate transition spans Kimmeridgian to upper Berriasian, according to Pszczolkowski and Myczyñski (2003). In this region, the lower terrigenous arkosic sequence (Constancia Formation) probably accumulated in small grabens, a tectonic scenario similar to that present in the southeastern Gulf (Pszczolkowski and Myczyñski, 2003). In the southeastern Gulf, Marton and Buffler (1999) dated the change from terrigenous to carbonate sediments as Kimmeridgian based on their interpretation of the Guaniguanico sections. However, they did not consider that, however related to the Gulf, in western Cuba the tectonic setting was different and upper Jurassic–Berriasian beds accumulated on a recently formed passive margin (Haczewski, 1976). Upper Jurassic beds from the Guaniguanico Cordillera, in the west, to Maisí in the east (Figure 1), record the first sediments deposited along the northern margin of the young proto-Caribbean Basin (Figures 3, 16) (Marton and Buffler, 1999). A complicated paleogeographic and paleotectonic evolution existed during the Kimmeridgian. According to Olóriz et al. (2003), a tilt-reversal affected the northern rim of the Gulf of Mexico Basin during the Kimmeridgian, forced terrigenous input in the southeastern United States, and was related to the assumed beginning of the differential subsidence of the central Gulf. This stratigraphic interval more or less coincided with deposition of the shallow-water carbonates of the San Vicente member. Block tectonics presumably affected western Cuba (Pszczolkowski, 1978) with local transgressions and regressions in a background of subsidence, whereas north-central Cuba underwent relative transgression (Placetas zone). Differential tectonoeustasy conditions terminated at the latest Kimmeridgian-earliest Tithonian when generalized transgression occurred throughout western and north-central Cuba. This comparatively sudden change in depositional conditions close to the Kimmeridgian–Tithonian boundary correlates with that registered at the northern rim of the Gulf of Mexico Basin, where Cotton Valley deposits rest on the youngest carbonates of the Haynesville Formation (Olóriz et al., 2003). Thus, the initiation of generalized transgressive conditions in the North American paleomargin of the proto-Caribbean Basin in Cuba contrasted with the opposite trend at the northern rim of the Gulf of Mexico Basin: an isochronous (in geologic, biostratigraphic sense) but differential response to a tectonic pulse affected the northern Gulf as opposed to the southern margins of the present Gulf (former North America-proto-Caribbean passive margin) (Olóriz et al., 2003).

Deeper depositional conditions started during the Tithonian along the paleomargin in northern Cuba. Possibly, this event can be correlated with the beginning of the drowning and stepback of the small carbonate platforms developed along the southeastern Gulf (Marton and Buffler, 1999; Moretti et al., 2003). A similar trend has been identified at the northern rim of the Gulf of Mexico Basin (Olóriz et al., 2003).

In the earliest Cretaceous, spreading and rifting ceased in the southeastern Gulf of Mexico (Marton and Buffler, 1994, 1999; Pindell, 1994, among others) when the Yucatan block reached its present position. Rapid

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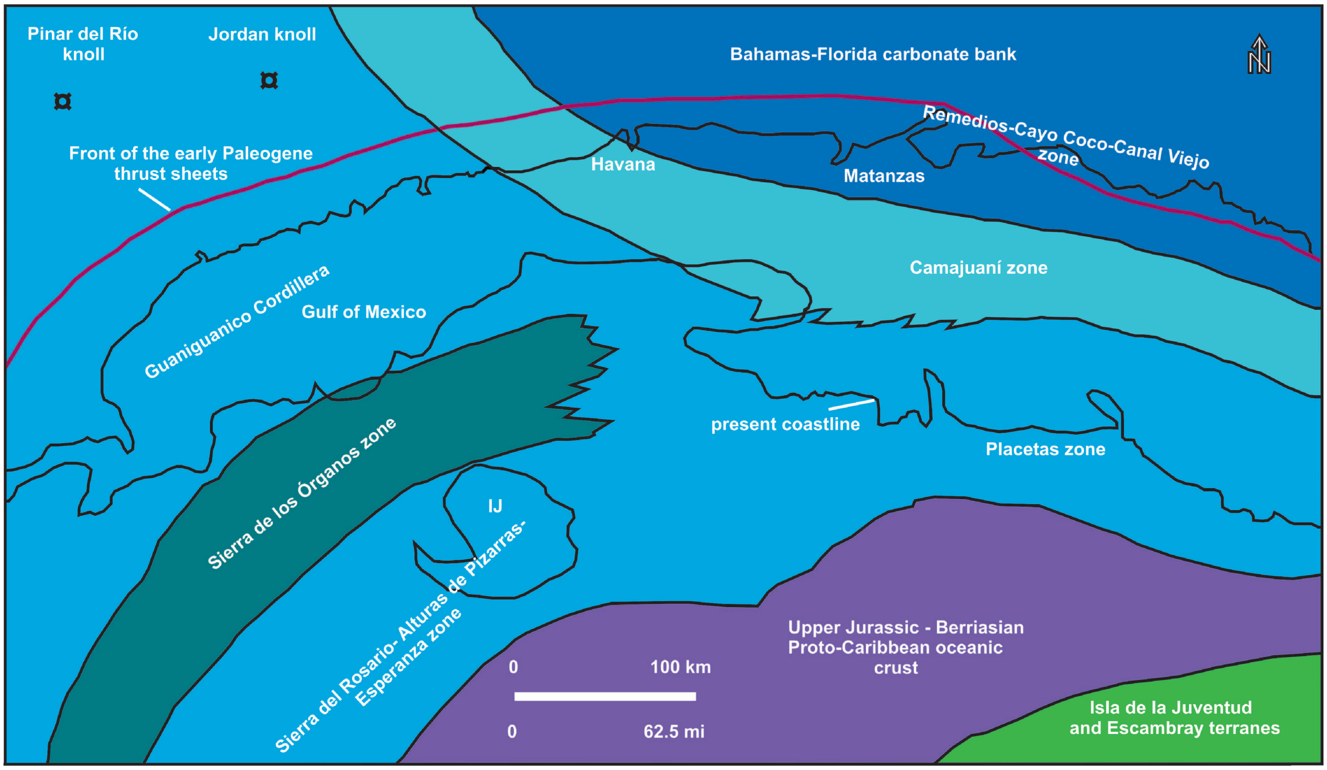

FIGURE 16. Berriasian palinspastic map of western and central Cuba and its surroundings. The figure includes some younger regional features: the overthrust front of the Cuban orogeny (late Paleocene–middle Eocene), the Pinar fault, and the Gulf of Mexico knolls. Except for the proto-Caribbean, the remaining units are blocks with thinned to normal continental crust. The western proto-Caribbean is interpreted as the oceanic crust created during the Oxfordian (or later)–Berriasian interval caused by separation from the North American paleomargin and southward drifting of a microcontinent whose margin consists of metasediments of the Isla de la Juventud and Escambray massifs (microcontinent?) (Cobiella-Reguera 2000). Estimates of horizontal displacements caused by the Cuban orogeny are from Pszczolkowski (1983) and Cobiella-Reguera (2005b).

thermal subsidence commenced in the entire area, and a marine transgression finally submerged the previously emergent blocks surrounding the Yucatan Platform. The unconformity that records the change in tectonic setting was called the late Berriasian surface (Marton and Buffler, 1999).

The updated interpretation of calpionellid biostratigraphy from leg 77 allows the correlation of events in Guaniguanico with the restructuring of the southeastern Gulf and adjacent areas during the latest Jurassic to earliest Cretaceous. In fact, no autochthonous sediments older than the Cretaceous have been recovered from leg 77, and they overlay fluvial and nearshore arkoses of probable Berriasian age (Watkins and McNulty, 1984). Our reinterpretation indicates that the age of generalized flooding in the area was middle Berriasian and not late Berriasian as stated by Marton and Buffler (1999). Their calpionellids in the basal marine beds indicate calpionellid zone C (i.e., late–middle Berriasian). Hence, basement highs in the southeastern Gulf (holes 536, 537) were at or near sea level during the early Berriasian, then drowned during the middle Berriasian. Basement areas close to western Cuba (hole 538 at the Catoche Knoll) might be considered to have a minimum age of late–middle Berriasian, although they were interpreted by Buffler, Schlager et al. (1984) and Schlager, Buffler et al. (1984) as including early? to late Berriasian rocks resting on an igneous basement in 538A. The lowest of these rocks, unit V, is oolitic, skeletal, oncolitic, and has minor pelagic limestones containing zone C calpionellids (bottom sample 538A-30-1) (Premoli-Silva and McNulty, 1984). Moreover, reworked *Crassicollaria brevis* in samples 538A-25 and 538A-26 could be early Berriasian instead of late Tithonian, as suggested by Premoli-Silva and McNulty (1984), on the basis of the relative abundance of this calpionellid species during these ages. These reinterpreted data correspond to a late–middle Berriasian restructuring event in the southeastern Gulf. This event was represented in the North American paleomargin in Cuba (northern proto-Caribbean area) by initiation of siliceous deposition (Figures 3, 13, Sumidero and Tumbadero members in Guaniguanico highlands

and, possibly, Margarita and Veloz [Ronda] formations in north-central Cuba) and resulted in a deepening phase. The early–middle Berriasian crisis interpreted by Marques et al. (1991) and widely recognized in the central North Atlantic Basin and the northern rim of the Gulf of Mexico Basin by Olóriz et al. (2003) correlates with this event, thus giving a regional context to the geodynamic significance of this tectonoeustatic event.

As Figure 16 depicts, in middle and late Berriasian, a belt of deeper water carbonates (Camajuaní, Placetas, Sierra del Rosario, and Sierra de los Órganos zones) surrounded the northern margin of the proto-Caribbean (western Tethys) at least from the present southern east-central Cuba to the northwestern Caribbean Sea and southeastern Gulf of Mexico.

CONCLUSIONS

Jurassic–Cretaceous rocks from the North American passive continental paleomargin crop out along northern Cuba. Coeval sections exist in metamorphic terranes at Escambray (central Cuba) and the Isla de La Juventud (Isle of Youth, southern Cuba).

Together with sedimentary records from the southeastern Gulf of Mexico, these sections reveal early stages of Pangea's breakup in Mesoamerica and concomitant early structuring in both the southeastern Gulf of Mexico and the proto-Caribbean (westernmost Tethys) areas.

The generalized occurrence of a lower terrigenous and an upper marine carbonate sequence reveals a major phase in paleomargin structuring. Shifting from terrigenous to carbonate sedimentation occurred during the late middle Oxfordian in western Cuba, and possibly in the Escambray mountains (central Cuba) area. In the Placetas zone of north-central Cuba, turnover from terrigenous to carbonate deposition progressed throughout the Kimmeridgian to Berriasian. All along northern Cuba, generalized transgression occurred close to the Kimmeridgian–Tithonian boundary.

The Yucatan block reached its present position early in the Cretaceous, and spreading and rifting ceased in the southeastern Gulf of Mexico. A middle Berriasian unconformity records this major paleogeographic change, which could relate to widespread cherty sedimentation across northern Cuba. Deep-water sedimentation along the southern paleomargin of North America and extensive carbonate banks on the Bahamas-Florida platform and surrounding the emergent Yucatan Platform developed during the middle and late Berriasian.

Correlation with major lithofacies shifts in both Mexico and the northern rim of the Gulf of Mexico indicates phase structuring affecting the whole Mexico-Caribbean area with differential regional expression.

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