Caribbean Journal of Science, Vol. 00, No. 0, 000–000, 2001

Geology of the Amber-Bearing Deposits of the Greater Antilles

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ABSTRACT.—Amber and associated lignitic rocks are known from Cuba (Miocene lignite), Haiti (Miocene lignite and traces of amber), the Dominican Republic (Miocene lignite and amber in exploitable quantities), Puerto Rico (Oligocene and Miocene lignite and traces of amber), and Jamaica (Maastrichtian-Paleocene amber). However, there is no modern review of the geology of the amber-bearing deposits and the data available is dispersed in many contributions. This paper fills this gap and presents the results of five years of original research on the subject. Greater Antillean amber probably derived from the resin of *Hymenaea protera*, an extinct leguminous tree which probably grew in evergreen forests. Amber is the consequence of diagenetic changes that operate in the resin after burial in the sedimentary pile, sometimes over 1000 m deep, where it is subjected to higher temperature and pressure over millions of years. The origin of unusually large Miocene deposits of amber in the Dominican Republic can be explained by the fortunate combination of adequate conditions of relief and soil for the development of a large populations of resin-producing trees during a constrained warm and humid climate optimum that occurred about 16 m.y. ago.

INTRODUCTION

Dominican amber was known by the natives of Hispaniola and was taken to Spain by Cristopher Columbus as one of the treasures of the West Indies. During the 20th century, Dominican amber became famous for the quality of its fossils, which include extremely well-preserved fungi, algae, plant remains, land invertebrates (arthropods, nematodes, gastropods) and land vertebrates (amphibians, reptiles, remains of mammals and birds) (Pérez-Gelabert, 1999).

Amber has also been reported from Haiti (Maurrasse, 1982), Puerto Rico (Iturralde-Vinent and Hartstein, 1998) and Jamaica (G. Draper, pers. comm.), but none of these occurrences has economic value. Despite widespread interest in amber, there is no modern review of the geology of the amber-bearing deposits of the Greater Antilles. This paper fill this gap by (1) reviewing the occurrences, age, stratigraphic position, and environment of deposition of the amberiferous beds; (2) presenting new information about the age and origin of the amber as a fossil resin; (3) discussing the paleogeographic scenario when amber-bearing deposits were formed; and (4) describing the fossil assemblage found not in the amber itself but in the associated deposits (Iturralde-Vinent and MacPhee, 1996; Iturralde-Vinent and Harstein, 1998).

WHAT IS RESINITE, RESIN, COPAL AND AMBER?

Resin-producing trees are widely distributed in the tropics, but amber in tropical America most probably derived from the resin of the extinct leguminous tree *Hymenaea protera*. Although several extant species of this genus occur from the Amazon Basin to Mexico, only two species occur in the Greater Antilles: the widespread *H. courbaril* L. (commonly known as courbaril in Cuba and as algarrobo in the Dominican Republic and Puerto Rico), and the northeastern Cuban endemic *H. torrei* León. The extinct amber-producing tree of the Dominican Republic was named *Hymenaea protera* by Poinar (1991). This taxon is related to *H. verrucosa* of western Africa and probably to *H. torrei* of eastern Cuba (Lee and Langenheim, 1975).

Resinite.—This is an all-encompassing

term for all types of plant-derived resins, regardless of age and physical or chemical characteristics.

Resin.—This term applies to material recently exuded from the tree and which has not been buried. Its physical and chemical characteristics depend on the species of tree. Resin can be sticky or dry and fragile. It can have a whitish or darker coating, but internally is transparent, yellowish, reddish, or brown. Resin is non-volatile, relatively inert, hydrophobic, amorphous, and strongly resistant to decay. Its decay (as well as that of copal and amber) is due to atmospheric exposure, and the material is best preserved when deposited in subaqueous or water-logged environments. Atmospheric weathering often produces opaque surface crusts and oxidation rims, and may cause an overall darkening of the resin grains (Tyson, 1995). Naturally exuded resin seems to be a physical surface barrier against infection by plant pathogens (Lee and Langenheim, 1975; Grimaldi, 1996).

Copal.—This is an older resin that can be found in the leaf litter layer or buried in the soil below the tree. It is usually solid, fragile, transparent with a dark surface coating, and internally yellowish, reddish, or brown. Copal of *H. courbaril* usually sinks in fresh water and floats in salt water (personal observation). Resin in the form of copal accumulates in forest soils and ombrogenous peat deposits, whose high (domed) water tables aid preservation.

Amber.—This is the fossil equivalent of copal. It is usually indurate, massive, and resistent to organic solvents. Amber can be transparent, but more frequently it is translucent with yellow, reddish, brown or blue-brown color. These characteristic are the consequence of diagenetic changes that operate in copal after burial in the sedimentary pile, sometimes at depths over 1000 m, where it is subjected to elevated temperature and pressure. Under these conditions and several millions of years, copal is naturally cooked and transformed into amber. Dominican amber usually sinks in fresh water and floats in salt water (personal observation).

After erosional exposure, copal and amber are frequently reworked and redistributed by flash floods and the normal fluvial and runoff processes. Amber can also be reworked by coastal erosion, as in the Baltic region (Schlee, 1990; Grimaldi, 1996). Amber clearly has significant potential for redeposition if protected from prolonged exposure to atmospheric oxygen. Langenheim (1990) indicates that near-flotation allows some amber particles to be readily moved by weak currents and tends to protect them from abrasion and fracture, even during prolonged transport. Amber is typically deposited in low energy bays, deltas, river mouths, estuaries, and other coastal areas. Large amounts may be carried further offshore as inconspicuous microscopic particles (Grimaldi, 1996).

The Amberiferous Deposits of the Greater Antilles

Amber and associated lignitic rocks are known from the Greater Antilles (Fig. 1) in Cuba (Miocene lignite), Hispaniola (Miocene lignite and amber), Puerto Rico (Oligocene and Miocene lignite and traces of amber), and Jamaica (Maastrichtian-Paleocene traces of amber). The following paragraphs describe the basins and sediments known to contain amber, regardless of their commercial importance. F1

Hispaniola

The Late Tertiary rocks of the Dominican Republic occur in a variety of geological contexts, predominantly of sedimentary origin, formed in subaerial to deep-marine depositional environments (see references in Mann et al., 1991). Amber in commercial quantities is well known from areas north of Santiago de los Caballeros and northeast of Santo Domingo (Fig. 1; Vaughan et al., 1922). These mining districts are known respectively as the Northern Area and the Eastern Area. Minor occurrences of amber have been reported from the Plateau Central-San Juán Area (Lemoine in Sanderson and Farr, 1960; García and Harms, 1988; Harms, 1990). All amber occurrences are of late Early to early Middle Miocene age and are associated with lignitic material, but

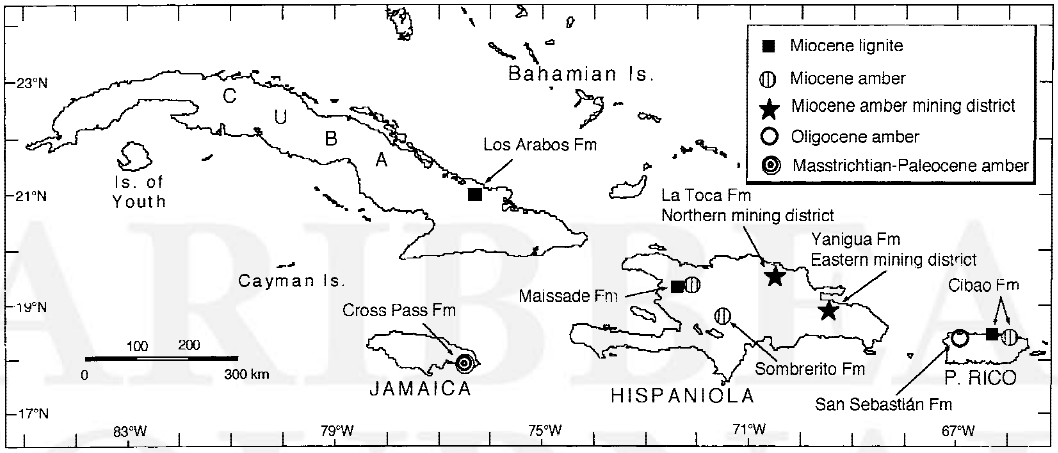

FIG. 1. Amber and lignite occurrences in the Greater Antilles. Lignite is not always associated with amber, but the opposite is true.

each represents different depositional environments, from terrestrial-marine transition to deep marine (Iturralde-Vinent and MacPhee, 1996).

Eastern Mining District

The Eastern Mining District is on the northern margin of the Cordillera Oriental, between Sabana la Mar, Hato Mayor, Bayaguana, and Cotuí (Fig. 2). The sedimentary rocks that form the substrate are mostly Neogene; along the west, south and east margins of the basins they directly overlay Cretaceous sedimentary, volcanic, and igneous rocks. On the northern side of the area, a W-NW trending fault is present along the edge of the Neogene limestone. The limestone on the northern block of the fault is overlain by Pliocene to Recent deposits. In general, Miocene rocks dip gently toward the north-northeast, so the thickness of the Neogene section varies from less than 100 m in the south to several hundreds of meters in the north (Brouwer and Brouwer, 1982; Toloczyki and Ramírez, 1991; Lebron and Mann *in* Mann et al., 1991).

Brouwer and Brouwer (1982) recognized four stratigraphic units in the Eastern Mining District: the basal conglomerates, the amber-bearing Yanigua Formation, the

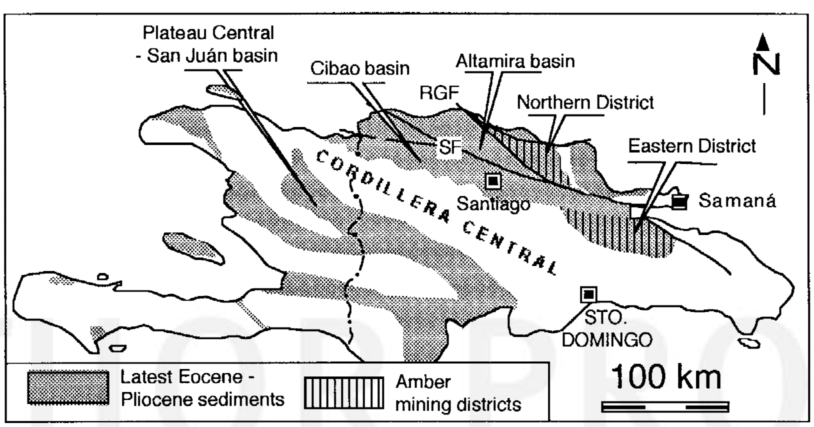

FIG. 2. Generalized geological map of Hispaniola showing the amber-bearing areas. Adapted from Iturralde-Vinent and MacPhee, 1996.

"*caliza* Cévicos", and the "*caliza* de los Haitises." According to some authors, there is only one limestone or *caliza* unit (Bowin, 1966; Toloczyki and Ramírez, 1991; Lebron and Mann *in* Mann et al., 1991). My field observations suggest that the limestones that Vaughan et al. (1922) named Cévicos are those found as intercalations in the upper part of the Yanigua Formation, and are not worthy of being differentiated as an independent unit. The basal conglomerates, as they occur intercalated with the other lithologies of the Yanigua Formation, are also incorporated to this unit. Therefore, only two formations are recognized in the Miocene basin: Yanigua formation (with the basal conglomerates) and Los Haitises F3 formation (Figs. 2 and 3).

YANIGUA FORMATION

The Yanigua Formation (Brouwer and Brouwer, 1982) is the amber-bearing unit of the eastern Area. Outcrops are located mostly around the present-day margins of the Neogene basin, at the localities of Antón Sánchez, Bayaguana, Comatillo, Colonia San Rafael, Yanigua, El Pontón, Sabana la Mar, and in several falls along the F4 Yanigua and Comatillo rivers (Fig. 4). Its thickness is calculated from the map as around 100 m.

The basal conglomerates have limited outcrops (Champetier et al., 1980) but may have an extensive distribution, as they were found in several bore holes drilled in the basin (Brouwer and Brouwer, 1982). The conglomerates are composed of poorly sorted subangular to subrounded elements contained in a fine grained matrix. Since fossils have not been reported, their age assignment remains problematic, but according to stratigraphic position it can be basal Miocene-Oligocene. Champetier et al. (1982) suggest that these conglomerates are frequent intercalations in the base of the Yanigua Formation in the Samaná area. They do not report fossils from these localities, but the association of conglomerates and lignite suggest that the basal conglomerates are a lateral, lowermost facies of the Yanigua Formation. Champetier et al. (op. cit.) reported no amber from this conglomerates. The sedimentary characteristics of the conglomerates (oblique lamination, formation of channels, erosional surfaces below the coarse grained beds) suggest a fluvial environment of deposition.

In general, the rest of the Yanigua section shows minor lateral differences (Fig. 4). Dark clays and laminated sandy clays containing fresh-water mollusks are the most common lithologies, along with lignite and carbonaceous clays and sandstones. Sandy clays may contain authigenic pyrite and are composed of 80-90 % mud and 10-20 % grains of calcite, calcareous earthy particules, detrital quartz, and igneous rock fragments. Laminae in the sandy clays are normally parallel, but can be slightly disturbed by micro-ripples and by isolated gravel inclusions that indicate local turbulent currents. These beds contain flattened and irregular inclusions of amber, usually as pockets or lenses ranging from a few millimeters to several centimeters in size, and may also contain fresh- to brackish-water ostracods and mollusks (see below).

The clays are typically dark gray-black, carbonaceous, with rare authigenic pyrite, almost without detritus, and with only some grains of calcite and quartz. They are usually fossiliferous and contain fresh- to brackish-water mollusks, ostracods, foraminifera, bryozoa, fish teeth, etc. (Tables 1 T1 and 2). Mollusk shells have been usually T2 fractured and flattened during diagenesis. Fossils of crocodiles, turtles and dugongs have been found in this context (Iturralde-Vinent and MacPhee, 1996). These amber-bearing beds contain abundant fragments of carbonaceous material that still shows textures of a vegetal nature. Although Brouwer and Brouwer (1982) report that all the amber from this source shows erosional features, all the specimens found by the present author have sub-rounded, oval or stalactite-like shapes representing the original form and not one caused by secondary erosion.

The lignite is found intercalated with the carbonaceous clays and sandy-clays. Lignite sometimes includes needles and crystalline aggregates of gypsum, probably originated during diagenesis. The lignite

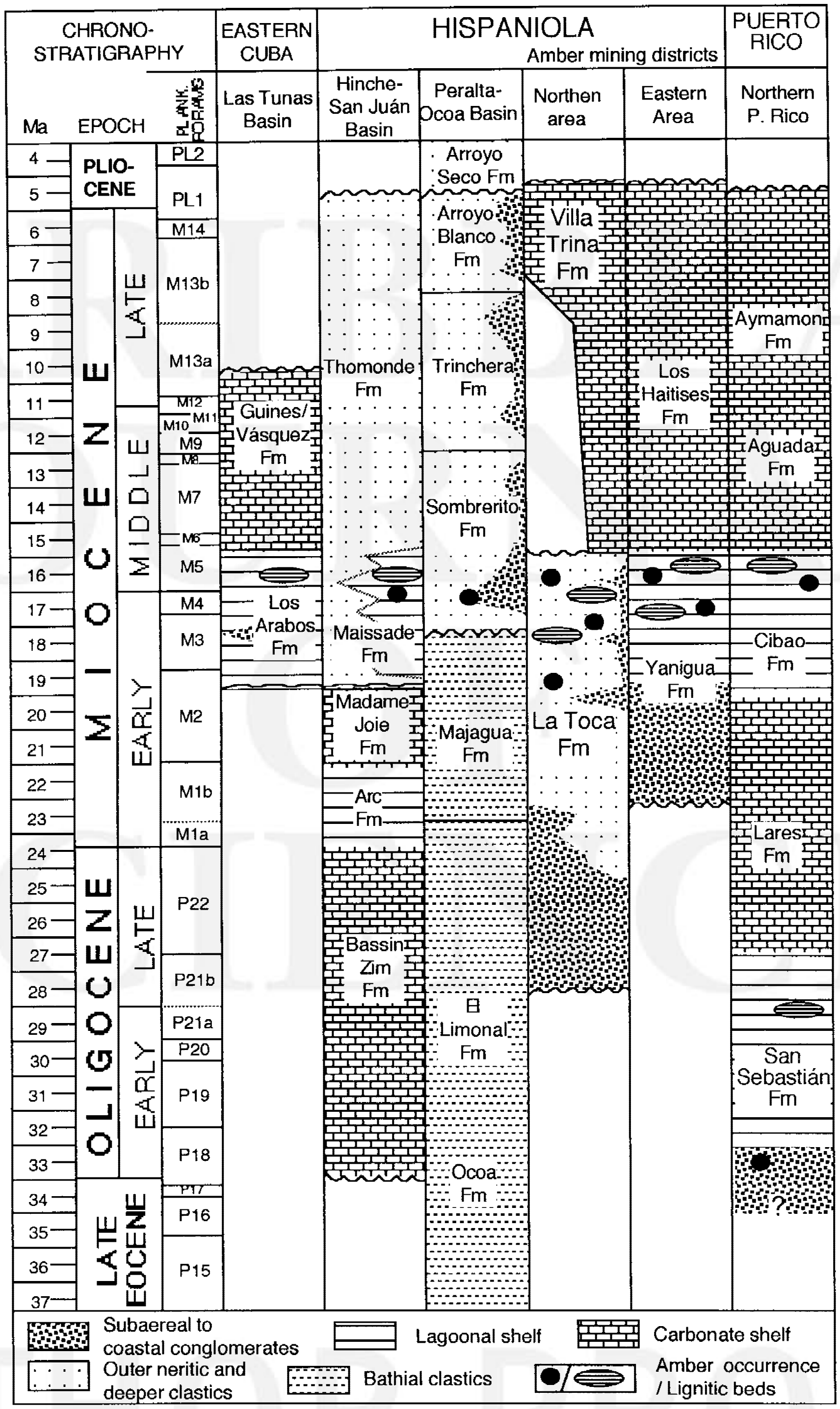

FIG. 3. Selected columnar sections of the Oligocene and Miocene Greater Antilles amber and lignitic-bearing rocks. Updated from Iturralde-Vinent and Hartstein, 1998.

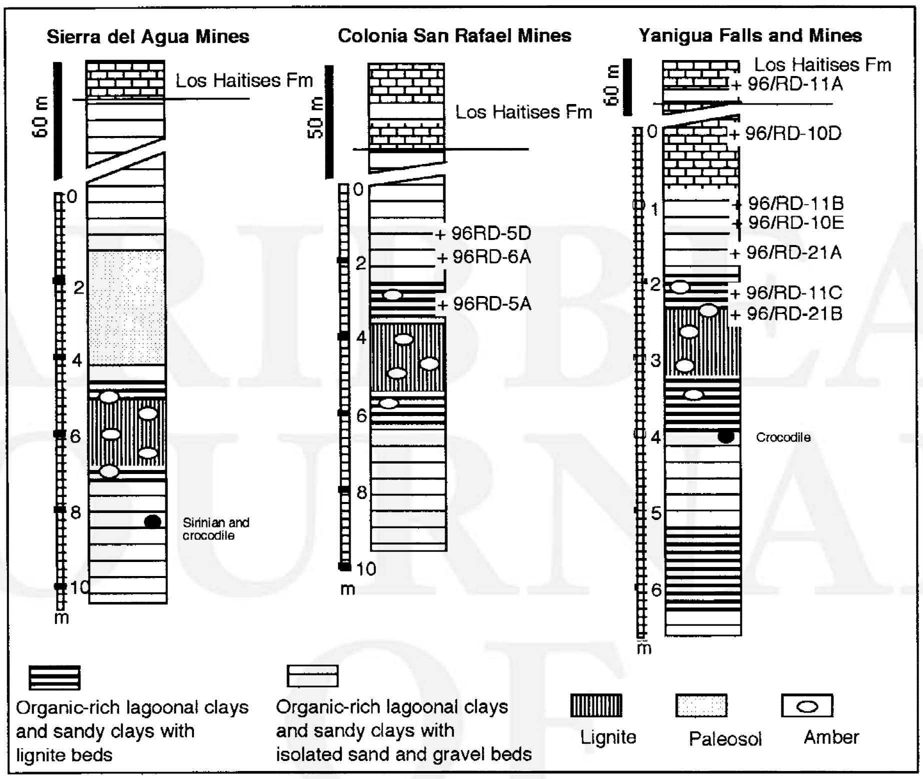

FIG. 4. Selected lithologic sections of the Yanigua Formation.

occurs usually as layers a few millimeters thick, but also occur as beds over 1 m thick. The lignite is hard, compact, and deep black with a metallic shine. No fossil inclusions, other than plant impressions on the surface of the beds, have been found. Bioturbation due to animal burrowing and plant root penetration is common in the lignite and related sediments. The burrows are vertical, sometimes with horizontal bifurcations, and they are filled with material from the layer above.

Locally in the area of Sierra del Agua is a well-developed 1 to 2 m thick, reddish paleosol clay layer, located near the top of the lignite. Coarse gravel and sand on top of the paleosol is also found in this region (Fig. 4). Dugong and crocodile bones have been recovered from the clays that underlie the lignite at this locality.

Environment.—According to Champetier et al. (1982) the section at Yanigua was formed in a low energy environment, which is the common type of section in the basin. Van den Bold (1988) studied the ostracods of two samples of the Yanigua Formation obtained from amber mines near Laguana and Bayaguana, and suggested that the association indicated a low salinity environment. Lithology, sedimentological features, and fossil composition clearly corroborate the opinion of Brouwer and Brouwer (1982) concerning the lagoonal to coastal marine depositional environment for most of the Yanigua Formation. This opinion was followed by Toloczyki and Ramírez (1991) when they described these rocks as “marls of littoral facies”.

Toward the top of the Yanigua Formation are beds of biocalcarenites, first intercalated with the clays (Cévicos limestone), but then dominating the section until the overlaying Los Haitises Formation. These biocalcarenites are very fossiliferous, with large foraminifera, algae, fragmentary marine mollusk shells, echinoids, bryozoa, corals, etc. They also show evidence of bioturbation due to animal burrowing and oxi-

TABLE 1. Microfossils from the amber-bearing Yanigua Formation. Samples investigated by Consuelo Díaz (96RD-10A, -10D), Gena Fernández (96RD-5A, -6A, 10E, 11A, 11B, 11C) and ostracods by W.A. van del Bold (96RD-6A, 10E, Bayaguana and Laguana). Blank space = not found.

Microfossils/Samples:	96RD-5A Colonia San Rafael	96RD-6A Colonia San Rafael	96RD-10A Yanigua	96RD-10D Yanigua	96RD-10E Yanigua	96RD-11A Salto del Yanigua	96RD-11B Salto del Yanigua	96RD-11C Salto del Yanigua	Bayagua na, Van den Bold 1988	Laguana Van den Bold 1988
Ammonia beccarii	x						x			
Ammonia beccarii ornata	x									
Ammonia beccarii parkinsoniana					x					
Amphistegina sp.										
Archaias angulatus				x	x					
Archaias sp.					x					
Elphidium advenum								cf.		
Elphidium cercadensis							x			
Elphidium lens		aff.					x			
Elphidium poeyanum	x									
Elphidium puertoricensis	x				x					
Elphidium sagra					x					
Elphidium sp.				x						
Miogypsina antillea				x		x				
Quinqueloculina polygona					x					
Quinqueloculina sp	x				x			x		
Triloculina sp.					x					
Coraline algae			x	x		x				
Corals			x							
Fish teeth							x	x		
Gastropods	x	x	x	x	x	x	x	x		
Pelecypods	x	x	x	x	x	x	x			
Equinoid spines		x		x	x					
Ostracods	x	x		x	x		x	x	x	x
Aurila amygdala		x			x					
Aurila galerita					x				x	x
Bairdia spp.					x				x	x
Baidoppilata willisensis					x					
Cativela sp. aff. C. moriahensis										x
Cushmanidea howei									x	x
Cytherella sp. aff. C. pulchra										x
Cytherella sp.									x	
Eucytherella sp.										x
Hemicyprideis agoiadiomensis						x	x			x
Hemicyprideis cubensis s.s.										x
Hemicyprideis stephensoni									x	

TABLE 2. Macrofossils identified by Paula M. Mikkelsen (AMNH) from Dominican Republic samples.

Sample	Mining area	Formation	Macrofossils	Habitat
96/RD-2A	Sierra del Agua	Yanigua	Large oyster	Lagoonal
96/RD-10E	Yanigua	Yanigua	Pectinidae, small Arcidae, small ?Veneridae	Marine
96/RD-21	El Pontón del Cuatro	Yanigua	Bivalves	Aquatic
96/RD-21B	El Pontón del Cuatro	Yanigua	Large Cardiidae or Arcidae	Marine
96/RD-18	El Cacao	La Toca	*Pisania?* or Turridae	Marine

dized plant roots, which suggests a marine shallow to coastal marsh environment. These succesions of strata record the transition from lagoonal deposition into carbonate shelf sedimentation (Yanigua through Los Haitises Formations).

Age.—The Yanigua Formation was dated as Miocene by Brouwer and Brouwer (1982), who report the fossils *Ammonia beccarii*, *Elphidium advenum*, and *Parocnus* sp. from Sierra del Agua. [Note: Since *Parocnus* is a Quaternary sloth, a photograph of the fossil, kindly provided by S. Brouwer, was examined along with additional material recovered from the same site. The study suggests that the fossil bones correspond to a Tertiary sirenian, probably *Methaxytherium*? sp. (Iturralde-Vinent and MacPhee, 1996)].

Toloczyki and Ramírez (1991) ascribed an Upper Miocene to Lower Pliocene age to the Yanigua Formation, while Lebron and Mann (*in* Mann et al., 1991) ascribed to it an Upper Miocene age (however, neither presented supporting paleontological data). Several samples collected by the author in different parts of the basin were examined for foraminiferans, ostracods, and nannofossils. The samples 96RD-10A, 96RD-10D and 96RD-11A were collected at the Yanigua river and in mines, from limestone beds intercalated near the top of the Yanigua Formation. The foraminiferal assemblages suggest a late Early Miocene age (Table 1, Fig. 4). The microfossils in samples collected 2-3 m below these limestones (96RD-10E, 11B, 11C; Table 1) and in Colonia San Rafael mines (96RD-5A, 6A; Table 1) are not as distinctive and suggest a late Early to Middle Miocene age. Van den Bold (1988) reported late Early to early Middle Miocene ostracods for two samples from Laguana and Bayaguana amber mines and corroborated this date with samples supplied by the author (Table 1). Therefore, the Yanigua Formation can be dated as late Early to early Middle Miocene (Miogypsina-Soritiidae zone of Iturralde-Vinent (1969)), or slightly younger, about 15 to 20 million years old according to the scale of Berggren et al. (1995).

LOS HAITISES FORMATION

The Haitises Formation (Brouwer and Brouwer, 1982) represents a shallow water shelf limestone overlying the Yanigua Formation. These limestones have been named Los Haitises or Cévicos in previous literature but Los Haitises is used herein. They are fossiliferous, containing mollusks (*Strombus* sp., *Kuphus* sp. and many others), corals (*Porites* sp., *Acropora* spp.), echinoderms, and algae. The age has been assigned without paleontological justification as Pliocene-Quaternary (Toloczyki and Ramírez, 1991), but Middle to Late Miocene is more likely because it rests conformably above the Yanigua Formation (Figs. 3 and 4). The thickness of the Los Haitises limestone can be estimated as 300 m minimum considering that it rests nearly horizontal and gives rise to steep karstic hills, some of them over 250 m high.

Northern Mining District

The Northern Mining District is located in the Cordillera Septentrional, north of Santiago de los Caballeros (Figs. 1, 2). This fault-bounded unit was designated as the La Toca Block (Dolan et al., 1991; de Zoeten and Mann, 1991), and part of the El Mamey Belt, represented by deformed Mesozoic and Cenozoic rocks. The La Toca block is limited today by the Camu, Septentrional, and Río Grande fault zones (de Zoeten and F5 Mann, 1991) (Fig. 5).

Originally, the La Toca Block was a part of a larger basin filled with Oligocene to Pliocene sedimentary rocks that unconformably overlies deformed and partially metamorphosed Lower Eocene and older igneous and sedimentary rocks (Toloczyki and Ramírez, 1991, Dolan et al., 1991; de Zoeten and Mann, 1991). The Late Tertiary deposits have been recently described as La Toca and Villa Trina Formations (Fig. 3; Dolan et al., 1991; de Zoeten and Mann, 1991). The amber-bearing deposits in the area are probably in the upper part of the La Toca Formation.

La Toca Formation

The La Toca Formation (de Zoeten, 1988) was originally described as a clastic Oligocene to lower Middle Miocene unit (de Zoeten, 1988; de Zoeten and Mann, 1991). It is equivalent to the Altamira facies of the El Mamey Formation of Eberle et al. (1980) (Fig. 5). The La Toca Formation has many similarities in composition, sedimentology, and age to the Oligocene to Early Miocene Maquey Formation of the Guantánamo Basin of eastern Cuba (Nagy et al., 1983; Calais et al., 1992; Iturralde-Vinent, 1994) and to the Thomonde Formation of the western part of the Plateau Central-San Juán area, but neither of these formations is amberiferous (Nagy et al., 1983; Butterlin, 1960; Maurrasse, 1982). The La Toca Formation was subdivided into three units that are characterized below according to de Zoeten (1988), with additional observations by the present author.

The lower conglomerate unit is about 300 m thick and corresponds with amalgamated conglomeratic facies and minor interbedded sandstones. Disorganized, matrix-supported facies and thinner, clast sup-

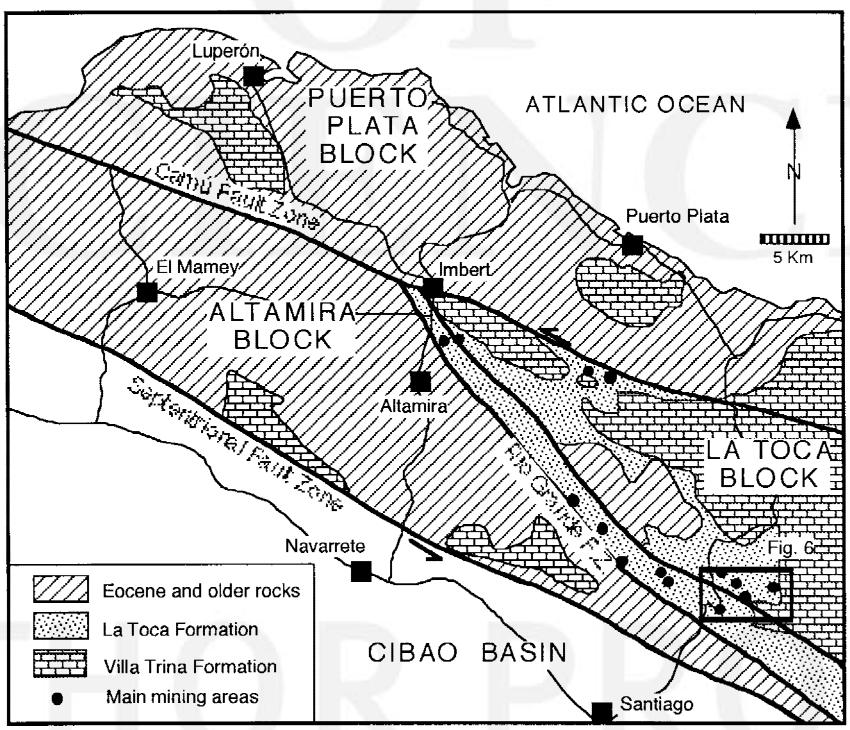

FIG. 5. Simplified geologic map of the northern mining district of the Dominican Republic. Adapted from several sources.

ported facies, comprise the lower 200 m of the unit measured by de Zoeten (1988) along the Río Grande section. Most beds are tabular, medium-bedded to massive, with planar basal contacts which rarely drape over clasts protruding from the underlying bed. The internal organization of the unit seems to increase upward in the section. In the later part, inversely graded facies are interbedded with clast-supported, parallel, stratified conglomerates. Clasts in the base range from granule to boulder in size. They are equidimensional to oblate in shape, and are subangular to rounded. The composition of the clasts near the outcrops of the underlying Pedro García Formation are about 70 % volcanic rocks (tuffs, andesites, and lavas), 20 % intrusives (tonalites) and 10 % sandstones, argillites, recrystalized limestone, quartz veins, serpentinite, and coral rudstones. This suggests that the major source for the clastics were uplifted lands with rocks like those of the Pedro García Formation. Such rock types are found not only in Cordillera Septentrional but also in Cordillera Central and Cordillera Oriental (Tolocczyki and Ramírez, 1991).

The flysch unit consists of alternating, thin- to medium-bedded, thinning-upward sandstones and shale couplets. A section measured by de Zoeten (1988) consists of 500 m of thick very thin- to medium-bedded sandstones and shales. The beds are tabular, laterally continuous, and exhibit sharp basal contacts. Basal sands are relatively coarse-grained, graded or structureless, and have mud-rich, massive, bioturbated upper divisions. A few thin- to medium-bedded, lens-shaped calcareous sandstone beds are interbedded with the sandstone and shale couplets. Higher in the section, lithic-rich calciturbidites and lithic conglomerates are interspersed between thin-bedded siliciclastic couplets. Together with the 1-2 m-thick conglomerate beds, calciturbidites form small (1-5 m thick) coarsening- and thickening-up cycles. The unit is laterally interbedded with the lower conglomerates. These deposits carry abundant planktonic foraminifera and nannofossils, as well as small benthic foraminifera typical of marine bathyal depth (500-1500 m) (Dolan et al., 1991).

The upper unit, 300 m thick according to de Zoeten (1988), is composed of thick-bedded sandstones with lesser amounts of conglomerate beds. Sandstone beds have high sand to silt ratios (2:1 to 10:1) and are commonly tabular, laterally continuous, and thick- to very thick-bedded (0.5 to 3.5 m). Basal sands range from gravel to medium sand in size. The lower divisions of the beds are coarse-tail graded, or massive, and grade up into parallel laminated sands rarely containing ripplemarks. Load casts are the dominant type of solemarks. The upper division in many beds contains concentrations of lignite and amber fragments that define parallel laminae in the siltstones. The finer fraction of the beds is mud-poor and parallel-laminated or massive. Considerable amounts of small carbonized plant fragments, including seeds, have been observed in these beds. The flysch and upper unit grade laterally into each other and become almost indistinguishable in the field.

Occurrence of amber:—Eberle et al. (1982) indicate that amber is always contained in lignite-rich sandstone beds or in lignite seams, and that considerable amounts have been mined from a few tens of meters above prominent conglomeratic horizons. However, according to Redmond (1982) amber is very rarely associated with the conglomerates and occurs in laminated, blue-gray, biotite-bearing siltstone with a rich organic content, sometimes concentrated in lignite stringers within the siltstone. Lignite beds are several inches thick at least in one location. Redmond also pointed out that amber-bearing siltstone is overlain almost always by thick, or more usually massive sandstones. This suggests that the amber was deposited in a mid-fan below the end of the channels, and that the massive sand from the channel was laid down later, prograding over the amberiferous bed. For Redmond, the amber seemed to occur in three to five horizons, suggesting that the it was deposited during a short period of time and not during all the time lapse of deposition of La Toca.

Several mining areas were visited by the present author to verify the position of amber in the La Toca Formation. In the Palo Alto Mine (Fig. 5), a section about 30 m thick was deposited under moderate energy and is composed of a set of complete or incomplete cycles of fine sand, carbonaceous silt, supracarbonaceous shale with amber, and infracarbonaceous shale and lignite (Champetier et al., 1982). Large fragments of amber, some weighing up to 13.6 kg, have been recovered from this mine. In La Toca Mine (Fig. 6), the beds overlying the amberiferous horizons are a set of 3-5 cm thick fine to coarse grained sands without gradation or coarsening upward. Two or three beds of conglomerates, up to 60 cm-thick, are intercalated in the section; they have a peculiar gradation from fine grains at the base to coarse grain in the middle and fine grains on the top. The amberiferous section is about 30 m thick and is composed of interbedded black, laminar, medium-to-fine grained sands and ligniferous silt. There are some thin beds of actual lignite measuring up to 5 cm thick. The section contains many carbonaceous plant remains and very small mollusks, both typical of a brackish water environment. The clastic materials in the rocks are composed of grains of igneous rocks and detrital minerals, including some quartz and calcite. The amber appears as flattened lenses, stalactites, and also as irregularly shaped, typically detrital fragments.

El Cacao Mine is located very close to La Toca, on the southern side of the same mountain range (Fig. 6). This site is particularly known for its unique blue amber. The amber-bearing section is about 20 m thick and is represented by fine grained, well-bedded (20-40 cm thick), black sandstone with some thinning upward gradation. The sandstone contain abundant small gastropods. Palo Quemado Mine (Fig. 6) is a few kilometers south of the previous mine. The section oberved is about 30-40 m thick and is represented by a well bedded, 10-20 cm thick stratum of fine grained, laminated, black sandstone. Coarse grained sandstone with carbonate cement is interspersed in the section. This sandstone became locally conglomeratic, as it contains isolated large pebbles within the matrix.

The section at Los Higos Mine is about 30 m thick and is represented by well-bedded, laminated, black, fine-grained sandstone

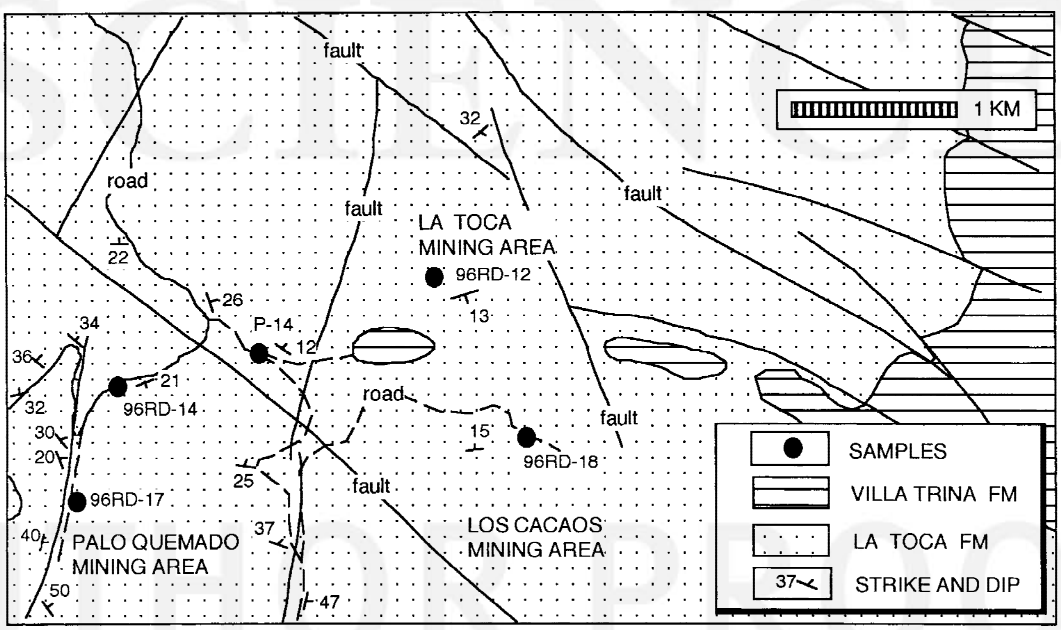

FIG. 6. Detailed geologic map of the La Toca, Palo Quemado, and Los Cacaos mining areas. Location in figure 5. Modified from de Zoeten (1988).

and silt, interspersed with coarse grained, 40-50 cm thick layers of sandstone and conglomerate. These beds are similar to those seen in La Toca, with a peculiar gradation from fine grains at the base to coarse grains in the middle and finer grains on the top, sometimes laminated, with intercalated lignite layers up to 2 cm thick. As in Palo Quemado, isolated pebbles are found on the very top of these beds. Amber occurs as irregular fragments, 20 to 40 cm long, embedded in the fine-grained rocks. Scattered fragments of lignite, approximately 6 cm long and 3 cm wide, are also present.

In all the mining areas visited, the amber is always associated with ligniferous material, and occurs in laminated sands and silts of deep marine environments. The amberiferous horizons occur within rock sections up to 40 m thick. Samples collected from these mines did not produced a precise date (up to the nanostratigraphic zone), so it was impossible to accurately correlate the sections from mine to mine. However, all the samples lie within the late Lower Miocene-early Middle Miocene interval, about 15 to 20 m.y. (Iturralde-Vinent and MacPhee, 1996). Therefore, it is possible to accept the conclusion of Redmond (1982), that all the amber mines are within the same stratigraphic level in the upper part of La Toca Formation.

Environment.—Composition and sedimentary features of the lower conglomerate unit suggest that they were derived from a local source, and probably laid down as rapid, cohesive debris flows in terrestrial to near shore environments; probably related to the active uplift of a highland area. However, the deposition of the flysch and upper amberiferous units took place in marine environments close to a fluvial plain with deltaic development.

According to Eberle et al. (1982), the lithological association of the flysch and upper unit of La Toca Formation point to a fan delta depositional environment, the amberiferous beds being deposited in interchannel flats, while marly units would represent the distal fan base environment. According to de Zoeten (1988), because vertical organization is lacking in the thick, tubular sandstone beds, it is unclear if the beds were deposited as lobes, channel-lobe transitional facies, or as delta front sands. Moreover, the microfossil assemblage and sedimentary features of the flysch unit suggested to Redmond and to de Zoeten and Mann that the beds were deposited as turbidity flows in a deep water basin. Northwest paleocurrent directions in La Toca and the isochronous Las Lavas Formations suggest that the sediment source was located toward the southeast (de Zoeten and Mann, 1991).

Lithological observations and paleontological evidence indicate that the flysch and upper units were deposited in a deep basinal environment located close to a forested mountain range. All the samples recovered from the previously mentioned mining areas contain planktonic and small benthic forams in associations suggesting a deposition depth over 500 m, probably 1000-1500 m (de Zoeten, 1988). The common presence of nannofossils agrees with this interpretation, although some of these fossils are redeposited from older beds.

Age.—No fossils have been found in the lower conglomerate, but its age is probably Oligocene-Early Miocene because the unit is typically at the base of the sections or partially interfingers with the flysch. The conglomerate probably represents a lateral equivalent of the basal conglomerate of the Yanigua Formation (Fig. 4).

Samples with microfossils reported by de Zoeten (1988) and Dolan et al. (1991), collected from different levels in the flysch, yielded ages of latest Oligocene and Early Miocene (7787, 10487, 13887; Table 3) and Early to Middle Miocene (P-14, D-229, 11587, 13187, 13487, 14087; Table 3). In the T3
Miocene samples there is some reworking from late Oligocene, which may suggest autocannibalism of the basin sediments. From the same localities (La Toca, Palo Alto, and Río Grande mines), Cepek (in Schlee, 1990) dated the rocks as Middle Eocene through Middle Miocene based on unlisted nannofossils (see also Grimaldi, 1995). The microfossils older than latest Oligocene found by Cepek are probably redeposited, since this process is common in the basin and samples taken from the same mines were dated as Miocene (see below).

TABLE 3. Microfossils from the La Toca Formation. Samples investigated by J.B. Saunders (16946–19648) in Baroni-Urbani and Saunders (1982); and P. MacLaughlin, E. Robinson and G. Monetti (P14 to RD3-229) in De Zoeten, 1988 and Dollan et al, 1991. Blank space = absent.

Microfossils/Samples:	16946	16947	16948	P14	7787	10487	11587	13187	13487	13887	14087	RD3-229
Amphistegina sp.	x	x										
Cassidulina subglobosa					x				x	x	x	
Cassigerinella chipolensis	x	x	x									
Catapsydrax dissimilis	x	x			x		x		x	x		
Catapsydrax unicavus	x											
Globigerina ciperoensis									x	x	x	
Globigerina selli							?		x	x	?	
Globigerina venezuelana		x	x		x				x	x		
Globigerinoides primordius								x	x			
Globigerinoides trilobus gr		x	x					?				
Globigerinoides tril. inmaturus	x											
Globorotalia obesa								x				
Globorotalia mayeri	x	x	x				x	x	x		x	
Globorotalia opima continuosa								?				
Globorotalia opima nana					x						x	
Globorotalia opima opima					x					x		
Globorotalia peripheroronda								?				
Hanzawaia sp.								x				
Pullenia bulloides										x		
Siphonina pulchra		x										
Siphonina tenuicarinata											x	
Spiroloculina depressa		cf.	cf.									
Uvigerina sp.	x											
Discoaster druggi						x						
Discoaster exilis												x
Discoaster variabilis												x
Heliscosphaera sellii												x
Sphaenolithus ciperoensis									x			
Sphaenolithus conicus									x			
Sphaenolithus heteromorphus				x								

Although microfossils are rare in the actual amber-bearing beds, several samples collected by the present author contain identifiable fossils. Sample 96RD-15, collected in the flysch several hundred meters stratigraphically below the La Toca mine area, yielded a poorly constrained Oligocene or Early Miocene assemblage (Table 4). The La Toca mine amber-bearing sandstone sample 96RD-12B carries a poorly preserved Oligocene or Early Miocene assemblage (Table 4). From just over the section at La Toca, sample 96RD-12C from the Villa Trina limestone yielded a very late Miocene or Pliocene assemblage (Table 5). Additional samples of different Miocene ages were identified using foraminifera from the Palo Quemado, El Cacao, and Los Higos mines (Figs. 5, 6; Table 4). This age range was corroborated by nannofossils (Table 4) from LaToca (96RD-12), Los Cacaos (96RD-18), and Los Higos (96RD-19 and 20). Only the results from Palo Quemado (96RD-17) samples are contradictory, since according to its nannofossils the sample is probably Late Oligocene and according to the foraminifera it is Miocene. However, both samples are poorly fossiliferous and the age assignments are not well constrained, being mostly based on absence of some index taxa.

Therefore, the entire range of the age of the La Toca Formation can be identified as Late Oligocene through Middle Miocene, as pointed out by de Zoeten (1988) and de Zoeten and Mann (1991); but the amberif-

TABLE 4. Microfossils from the La Toca Formation. Samples investigated by Timothy L. Bralower (nannos), Gena Fernández (forams) and Rafaela Perez (forams) for this paper. Blank spaces = absent.

Microfossils/Samples:	96RD-12B	96RD-12W	96RD-13A	96RD-15	96RD-17W	RD96-17X	96RD-17Z	96RD-18A	RD96-18B	RD96-19A	96RD-19B
Amphistegina sp.	x					x			fragm	x	
Amphistegina angulata										x	
Amphistegina gibba						?				x	
Globigerina angustiumbilicata				aff.							
Globigerina tripartita s.l.	x										
Globigerinoides altiaperturus									x		
Globigerinoides primordius									x		
Globigerinoides sp.				x		x			x		
Globigerinoides ruber									x		
Globigerinoides trilobus gr											
Globigerinoides tril. inmaturus											
Globorotalia archeomenardii									x		
Globorotalia obesa									x		
Globorotalia sp.				x							
Globoquadrina altispira altispira									x		
Globoquadrina altispira conica									x		
Gyroidina soldanii			x								
Nodosaria spp									x		
Praeorbulina transitoria											
Quinqueloculina sp.						x					
Rectobulimina sp.									x		
Uvigerina sp.											
Dictyococcites bisectus					x		x				
Sphaenolithus belemnus								x			
Sphaenolithus ciperoensis					x		x				
Sphaenolithus heteromorphus		x									x
Gastropods			x								

erous beds are more probably restricted to the upper half of the formation, which is late Early to early Middle Miocene in age (Iturralde-Vinent and MacPhee, 1996).

VILLA TRINA FORMATION

The Villa Trina Formation (Vaughan et al., 1922) is composed of shallow marine marls and calcarenites resting unconformably above La Toca Formation (Figs. 3, 5). The base of the unit is coincident with a basal conglomerate (Eberle et al., 1982). The age of the limestone has been assigned as Middle Miocene to Pliocene (de Zoeten and Mann, 1991), but samples of the Villa Trina limestone collected by the author (Table 5) yield assemblages of Late Miocene and Pliocene age. The thickness of the limestone unit can reach several hundred meters as can be inferred from present day topography.

Plateau Central-San Juán area

This basin, unlike those previously described, is located south of the Cordillera Central in southwestern Hispaniola (Fig. 2). The depression was filled with Late Tertiary clastic and carbonate sediments, many hundred meters thick, which show important differences in environment of deposition (Fig. 3). Only the Sombrerito and Maissade Formations, which contain amber and lignite, are described here. García and Harms (1988) and Maurrasse (1982) provide more information about this area.

SOMBRERITO FORMATION

The Sombrerito Formation is mostly developed in the eastern part of the Plateau Central-San Juán Basin (Fig. 2). It is represented by about 500 m of pelagic limestone, marls, and calcarenite. The marls are rich in pelagic and small benthic microfossils. Calcarenites are coarse to fine grained, graded, with sedimentary features indicating turbidity current origin. Sedimentary features and microfossils suggest that the formation was deposited in a lower slope, middle bathyal setting open to the sea. The formation has been paleontologically dated as late Early to early Middle Miocene (N8 - N12) (García and Harms, 1988).

It should be emphasized that this unit generally lacks detritus from older rocks, suggesting that little erosion of the catchment area was taking place at the time of the Sombrerito Formation deposition (García and Harms, 1988). The detritus material in the calcarenites is dominated by isochronous shallow water organic fragments derived from a carbonate shelf and coral reef environment. Nevertheless, the calcarenites that crop out east of Presa Sabaneta contain isolated fragments of amber (3 × 1 cm) associated with small remains of carbonized plants and detrital grains of quartz, plagioclase, and probably glauconite (García and Harms, 1988; Harms, 1990). This clearly indicates that local erosion was taking place in the catchment area of the basin, but the size and type of the detritus suggests that the source area was a low land mass. This sedimentary environment contrasts with that of the amber-bearing La Toca Formation, which corresponds to a clastic-dominated section representing extensive erosion of a highland source.

Maissade Formation

The Maissade Formation (Jones, 1918) occurs near the town of Maissade in central Haiti, and over the southwestern part of the Plateau Central-San Juán Basin. Lemoine (in Sanderson and Farr, 1960) reported traces of amber in a sample recovered from a well drilled in the Maissade area (Figs. 2, 3). The formation consists of 200 m-thick clay, shale, marl, gypsum, some sandstone, and characteristically lignite beds. The lower part of the unit is blue clay containing shallow water marine mollusks (*Turritella* sp., *Arca* sp., and *Ostrea* sp.), overlain by black carbonaceous shale, hard shaly sandstone, lignite, lignitic gray clays, gray sandy shales, gray argillaceous marls, blue clays, and some gypsiferous horizons. These beds usually contain the brackish-water mollusks *Potamides* sp., *Hemisinus* sp., *Hydrobia* sp., *Nerita* sp., *Scapharca* sp., and *Mytylopsis* sp. (Woodring et al., 1924; Butterlin, 1960; Maurrasse, 1982).

The Maissade Formation overlies with a local unconformity the latest Oligocene-lowermost Miocene Madame Joi Formation, and is overlain in turn by the Pliocene Hinche Formation (Butterlin, 1960; Maurrasse, 1982). The Maissade is generally considered a lateral facies of the Thomonde and Las Cahobas Formations (Bermúdez, 1949). The age of the Maissade is therefore late Early Miocene to Middle Miocene (Butterlin, 1960), but some beds similar to Maissade can probably reach the Pliocene (Maurrasse, 1982).

The Maissade represents an initial shallow marine landward invasion followed by a coastal-swamp environment (Woodring, 1922; Woodring et al., 1924; Maurrasse, 1982). In many respects, the Maissade Formation resembles the amberiferous Yanigua Formation of the Dominican Republic, the Cibao Formation of Puerto Rico, and the Los Arabos, Lagunitas, and Magantilla Formations of Cuba, although amber has not been reported from these last units.

Puerto Rico

Amber has been discovered in two localities in Puerto Rico, one of Oligocene and the other of Miocene age. The Oligocene amber is a tiny droplet recovered by the author in 1999 from ligniferous clays of the San Sebastián Formation near Lares (Figs. 1, 7). Miocene amber was collected from a F7
well south of the Cementerio Nacional in San Juán (Fig. 7). At the latter locality the amber occured in gray-blue marl and sandstone of the upper part of the late Early to early Middle Miocene Cibao Formation (Iturralde-Vinent and Hartstein, 1998).

Two small pieces of Miocene amber have been collected from the same horizon. One piece (originally 20x30x15 mm) is a some-

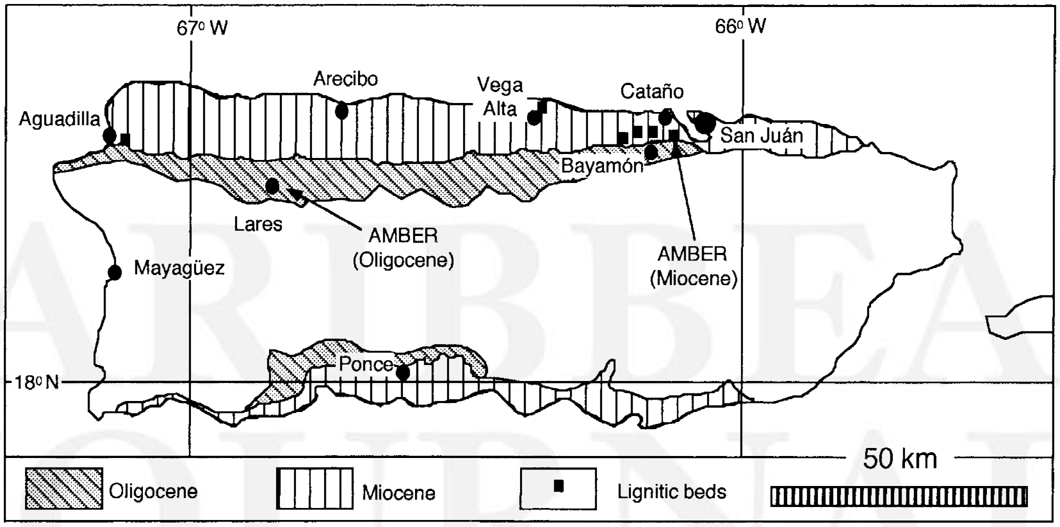

FIG. 7. Generalized geologic map of Puerto Rico showing lignitic and amber occurrences. Updated from Iturralde-Vinent and Hartstein, 1998.

what flattened, deep red, transparent fragment, with subangular edges suggesting that it experienced some transportation. The piece is brittle, has several fractures, and resembles low quality amber from the eastern mines (Yanigua and Colonia San Rafael) of the Dominican Republic. The fragility and low density of the Puerto Rican amber suggest that it suffered slight diagenetic transformation. This is confirmed by the presence of non-crystalline lignitic beds in the same stratigraphic position as the amber. The Miocene lignitic and amberiferous beds are within the transitional Early to Middle Miocene upper part of the Cibao Formation. Features common to all these lignitic occurrences are the deep black color of the sediment, the presence of fresh water mollusks, and the position within the uppermost part of the Cibao Formation near the contact with Aguada limestones (Iturralde-Vinent and Hartstein, 1998). In these beds there are shark, ray, and barracuda teeth, other unidentified fish elements, crocodilian teeth and vertebrae, sirenian ribs and vertebrae, and many turtle scuts.

CUBA

Amber has not been discovered in Cuba, but Miocene ligniferous rocks occur in the Los Arabos and equivalent Formations (Iturralde-Vinent, 1969). The best occurrence has been reported in the Las Tunas basin of eastern Cuba (Figs. 1, 3), where the Neogene strata unconformably overlie Eocene and Cretaceous rocks within a low relief plain. In this basin, the Early to Middle Miocene Los Arabos Formation is represented by more than 130 m of marls, calcareous clays, and marly limestones, with thin lenses of gypsum. Some isolated beds of lignite and plant-bearing clays are found. Clays are more common toward the bottom of the unit, while carbonate material is more abundant in the upper region. Pyrite and microfossils with pyrite-filled chambers are common like in the Yanigua Formation. The biocenosis includes fresh and brackish water forams, ostracods, mollusks, and echinoids. The Los Arabos Formation is conformably overlaid by more than 80 m of the Guines/Vásquez Formations, represented by Middle Miocene shallow-water marine limestone (Iturralde-Vinent, 1969).

The resin-producing tree *Hymenaea torrei*, the closest relative of *H. protera* and *H. courbaril*, occurs today in eastern Cuba (Bisse, 1988).

JAMAICA

The oldest occurrence of amber in the Greater Antilles, from the Maastrichtian-

Paleocene Cross Pass Formation of Jamaica, was reported recently to the author by Grenville Draper (pers. comm.). According to Draper, during a field trip led by Geoffrey Wedge in 1971, they found some pieces of dark brown amber with many dark inclusions, within a bedding plane of the well-bedded shales of the Cross Pass Formation. The amber was found at a small waterfall, close to the Indian Cony River near Bath in the Blue Mountains. According to Wadge and Draper (1978), the Cross Pass Formation is a deep marine well bedded with arenaceous to argilaceous cyclic turbidites, with many intercalated beds of coarse volcaniclastic sandstones. The unit was dated as Maastrichtian-Paleocene according to its stratigraphic position and the occurrence of reworked latest Cretaceous microfossils (*Pseudorbitoides*? *rutteni rutteni* and *Globotruncana* sp.) (Krijnen and Lee Chin, 1978).

This isolated occurrence of amber in the Blue Mountains is important because it is the oldest from the Caribbean realm. However, the specimens are not available for study and their origin from a leguminous or other tree cannot be determined. Additional search should be conducted within the outcrops of the Cross Pass Formation to collect more amber.

Age of the Greater Antillean Amber

The precise determination of the age of the amber deposits is very important because current data suggests that Dominican amber has the same age as the sediments where it is found, and because the age generally coincides with a climate maxima dated elsewhere as 16 m.y. (Tsuchi, 1990) which may have enhanced resin production.

Several authors have proposed that Dominican amber may be older than the strata in which it occurs, from Cretaceous (Brouwer and Brouwer, 1982) to pre-Lower Miocene (Baroni-Urbani and Saunders, 1982). This has been discussed in papers by Grimaldi (1995) and Iturralde-Vinent and MacPhee (1966), who concluded that there is no solid data to indicate that amber has been redeposited from older deposits. However, lack of redeposition from older rocks does not rule out that contemporaneous relocation may have taken place during the transportation of copal from the forest litter to the final repository.

Arguing against redeposition from older deposits is the fact that Dominican amber has not been reported, in large amounts, from rocks of indisputable Cretaceous, Paleocene or Eocene age. The only Oligocene report is a tiny droplet found by the author in ligniferous clays of the San Sebastian Formation in Puerto Rico, and this is no proof that there were amberiferous Oligocene sediments in the Greater Antilles. Furthermore, since Eocene and Oligocene rocks are not exposed in the catchment areas of the eastern mining district (Brouwer and Brouwer, 1982; Toloczyki and Ramírez, 1991) they cannot be the source of older amber, if such amber deposits ever existed. Paleogene rocks occur in the Cordillera Central and Cordillera Septentrional of Hispaniola, west and south of the northern district, but they do not contain amber (Fig. 3). Also, the mean paleocurrent directions measured in the La Toca Formation (Dolan et al., 1991) suggest that those Paleogene rocks were not the source of the clastic material in the amberiferous deposits. These measurements suggest that sediments in the northern district were derived from a source located southeast, which points to the same catchment basin that produced the eastern district sediments (see also Iturralde-Vinent and MacPhee, 1996).

In connection with the age of Dominican amber, it is important that organisms preserved in amber can almost always be allocated to extant groups at low hierarchical levels and many seem to differ little from relatives living in Hispaniola today (cf. Baroni-Urbani and Saunders, 1982; Grimaldi, 1995, 1996; Poinar and Poinar, 1999). If Dominican amber is of late Mesozoic or Paleogene age, more primitive faunal elements should be well represented (Grimaldi, 1996). For all these reasons, it is logical to conclude that Dominican amber is of the same age as the sediments that contain it; that is, that redeposition of amber of different ages did not occur (Iturralde-Vinent and MacPhee, 1996).

This conclusion does not, however, agree with efforts to date amber using exomethylene resonance signatures visualized by nuclear magnetic resonance spectroscopy (NMRS) (Lambert et al., 1985). To derive an age assessment by this method, resonance intensity must first be calibrated against NMRS results for specimens of known age. The only calibration curve (Lambert et al., op. cit.) relevant to the dating of Dominican amber is based on two data points: amber from Palo Alto mine (northern district), accepted as Early Miocene because sediments yield microfossils of that age (Baroni-Urbani and Saunders, 1982); and a resin sample from *Hymenaea coubaril*. Age estimates based on this curve (Lambert et al., 1985) indicate a Late Eocene age for amber recovered from mines at La Toca and Tamboril in the northern district, and a Middle Miocene age for specimens from Bayaguana and Cotuí in the eastern area. Microfossil evidence supports a Miocene age for amber-bearing sediments in the mines at Bayaguana (Van den Bold, 1988), but microfossils also establish that the La Toca mines are Miocene, which contradicts the NMRS results. If amberiferous sediments at La Toca, Palo Alto, and Bayaguana are paleontologically equivalent in age, then the exomethylene decay curve does not produce meaningful results (Grimaldi, 1996; Iturralde-Vinent and MacPhee, (1996).

The most interesting aspect of the Miocene amber found in Puerto Rico is that it was found in the uppermost part of the Cibao Formation, dated as Early to Middle Miocene (with large *Sorites marginalis* and the absence of *Miogypsina* sp. and *Lepidocyclina* sp., which occur stratigraphically below). The Cibao Formation underlies the Middle Miocene Aguada Formation (with *Archaias angulatus*, *S. marginalis*, and *Peneroplis* sp.) (Monroe, 1980; Iturralde-Vinent and Hartstein, 1998). These data place the Miocene amber-bearing bed of Puerto Rico within the same time frame as those of Hispaniola (Fig. 3).

Paleogeography

Having established the age of the amber in Hispaniola and Puerto Rico (Cibao Formation) as late Early to early Middle Miocene (20-15 m.y., probably close to 16 m.y.), the next step is to produce a paleogeographic map to determine the origin of the amber. Several attempts have been made to produce a paleogeographic reconstruction and historical geologic interpretation of the Greater Antilles during the Late Tertiary, but although authors were well aware of plate tectonics, they produced essentially fixist reconstructions (Maurrasse, 1982). Plate tectonic reconstructions such as those of Calais et al. (1992) or Pindell (1994) are directed to solving geometric problems of terrane location and not of physical geography (relieve). Only recently has there been an attemp to presented maps combining tectonic reconstruction and physical paleogeography (Iturralde-Vinent and MacPhee, 1996, 1999). Developing this theme, three maps are presented to illustrate the paleogeographic scenario of the Greater Antilles before, during, and after formation of the Dominican amber (Fig. 8). The data to construct these maps were compiled by Iturralde-Vinent and MacPhee (1996, 1999) and Iturralde-Vinent (1969).

Paleogeography during the amber epoch

The paleogeographic reconstruction presented here displays the Greater Antilles Ridge as subdivided into several groups of islands separated due to the presence of a shallow water shelf surrounded by moderate to deep water channels or basins. The first scenario for the Late Oligocene (27-25 m.y.) displays three main archipelagos as Western Cuba, Central Cuba and eastern Cuba-Cordillera Central-Puerto Rico-Virgin Islands (Fig. 8). These insular groups F8 changed little until the Early-Middle Miocene (Fig. 8: 16-14 m.y.), when separation between eastern Cuba and Hispaniola-P.R.-Virgin Islands became apparent due to activity along the Oriente fault (MacPhee and Iturralde-Vinent, 1995). It is at this time when resin was produced in large quantities in northern Hispaniola and in small amounts in southern Hispaniola and northern Puerto Rico. During the Middle Miocene (Fig. 8: 12-10 m.y.) the subdivision of eastern Cuba and Hispaniola was com-

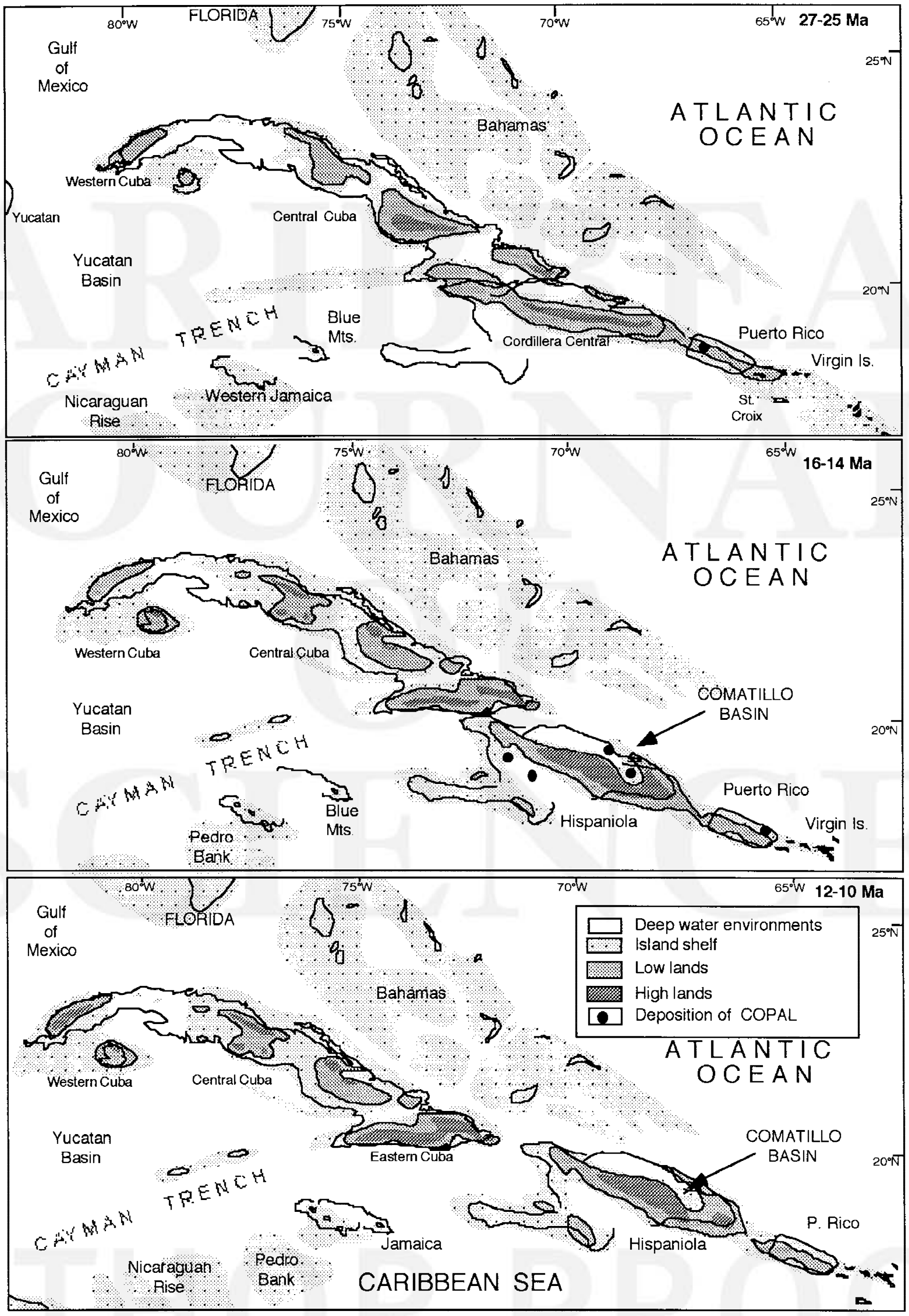

FIG. 8. Paleogeographic maps of the Greater Antilles for the Late Oligocene (27-25 m.y.), Lower Miocene (16-14 m.y.) and Middle Miocene (12-10 m.y.). Updapted from Iturralde-Vinent and MacPhee (1999) including a new map.

pleted and resin production had declined and stopped within the interval; a probable cause being a climate change induced by the new oceanographic scenario that arose from the opening of a marine channel between eastern Cuba and the Cordillera Central of Hispaniola.

In the early Neogene, the terranes of northern Hispaniola were located west of their current positions, closer to present-day southeastern Cuba. Then, the eastern and northern mining districts were part of the same structural depression, located north of the ancestral Cordillera Central. Their present (Holocene) position is due to post-Oligocene left-lateral displacement along the northern Caribbean plate boundary. It is proposed here that the paleogeographic basin represented by both the northern district and the eastern district during the Neogene be called the *Comatillo Basin* (Fig. 8) because there is no such feature today in the geography of the island.

The relief and configuration of paleo-Hispaniola was very peculiar in the Early to Middle Miocene (16-14 m.y.). A large uplifted ridge that includes present-day Montagnes Noires, Cordillera Central, Cordillera Oriental, and continued into Puerto Rico and the Virgin Islands was at that time the largest land mass in the Greater Antilles. Several small islands formed an archipelago south of the Plateau Central-San Juán Basin, and westward another large island was present which is represented today by southeastern Cuba (Fig. 8). The relief of these islands was differentiated with low and high topography. Some mountains were present west of the Comatillo Basin embayment and were the source for the huge amounts of clastics deposited in the structural depresion known today as La Toca block and the Cibao basin (La Toca and Baitoa Formations). Highlands were also present in southeastern Cuba and provided the clastic deposits of the Maquey and Imías Formations (Nagy et al., 1983; Fig. 3).

The mountains in both source areas were dissected by small rivers that discharged into the littoral plains, giving rise to siliciclastic ramps were alluvial fans and deltas typically developed. Massive coarse-grained debris flows that deposited thick conglomeratic beds in the littoral and basin areas occured locally. The rest of the uplifted territory was probably lowland, as the seashore was characterized by lagoons and mangrove swamps. These fresh to brackish-water lagoons were filled with very fine-grained sediments, resulting from slope-wash drainage of the surroundings areas. There were locally small rivers that deposited some gravel and coarser clastics.

The plant-derived organic debris in the amber and in the clastic rocks north of the Hispaniolan paleo-island suggest that the highlands were covered by humid tropical forest, like that which exists today on the windward side of higher elevations throughout the Greater Antilles. Humid forests also occurred in the lowlands facing the lagoonal-mangrove swamp coastal areas, as suggested by the common occurrence of lignite and the high organic content of the sediments.

The ecological interpretation of the amber biota (Grimaldi, 1996; Poinar and Poinar, 1999) and the presence of amber in the sediments, indicate that *Hymenaea* trees were abundant in the humid forest surrounding the Comatillo Basin (Fig. 9) on the northern slope of the Hispaniolan paleo-island. The presence of some amber in the Sombrerito, Maissade, and Cibao Formations suggest that some *Hymenaea* trees were also present in the southwestern slope of the Hispaniolan area and in the northeastern slope of the Puerto Rican area.

Origin of the Miocene Amber

Miocene Hispaniolan and Puerto Rican lignitic and amber deposits occur within the same time interval as Miocene lignitic deposits of Cuba (Fig. 1). This suggests that the unusual accumulation of Early to Middle Miocene amber and lignitic deposits was correlated with a non-sedimentological event, probably a warm climatic optimum (Tsuchi, 1990). However, a single factor is not sufficient to explain the production and accumulation of large deposits of amber, as demonstrated by the uniqueness of the commercially exploitable amber deposits of the Dominican Republic (Schlee, 1990; Grimaldi, 1996).

There are important differences between the Miocene lignitic lagoonal deposits of the Dominican Republic and those of Cuba, Haiti, and Puerto Rico. These differences are the state of diagenesis and the thickness of the lignitic beds. Lignite in the Yanigua Formation of the Dominican Republic is more crystalline and thicker than in the other deposits (Los Arabos, Magantilla, and Cibao Formations). This suggests a larger primary accumulation of plant remains in the original basin and deeper post-depositional burial. The lignite found in Cuba, Haiti, and Puerto Rico is not crystalline and occurs in thin beds generally represented by ligniferous clays.

The author believes that the occurrence of important concentrations of amber in the mining districts of the Dominican Republic is due to the combination of several factors that are considered in the following paragraphs (see also Figs. 9 and 10). F10

The *botanical factor* is the unusual abundance of a peculiar species of *Hymenaea*, presumably *H. protera*, in the Early Neogene of the Greater Antilles. This species produced large amounts of resin resistant to weathering and biological degradation. After segregation, the resin was polymerized, transformed into copal (Langenheim, 1990), and accumulated in the ground with other plant debris as part of the organic-rich litter (Fig. 10A; Grimaldi, 1996). The occurrence of abundant plant and solid inclusions in the amber, as well as present day accumulation of copal in the soil around *H. courbaril* trees, demonstrate the importance of this factor.

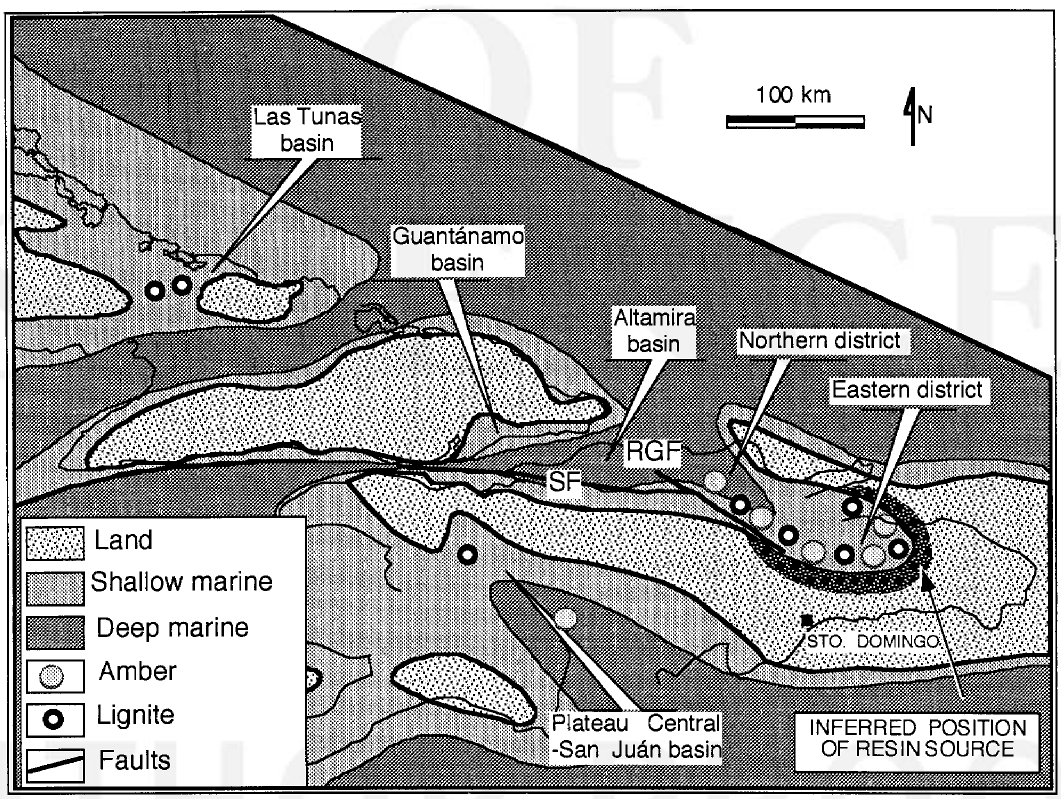

FIG. 9. Paleogeographic map of eastern -Hispaniola during the deposition of copal in the Comatillo basin (marine embayment embracing the northen and eastern mining districts restored to their Miocene -16-14 m.y.- paleogeographic position). SF Septentrional fault, RGF Río Grande fault. Modified from Iturralde-Vinent and MacPhee, 1996.

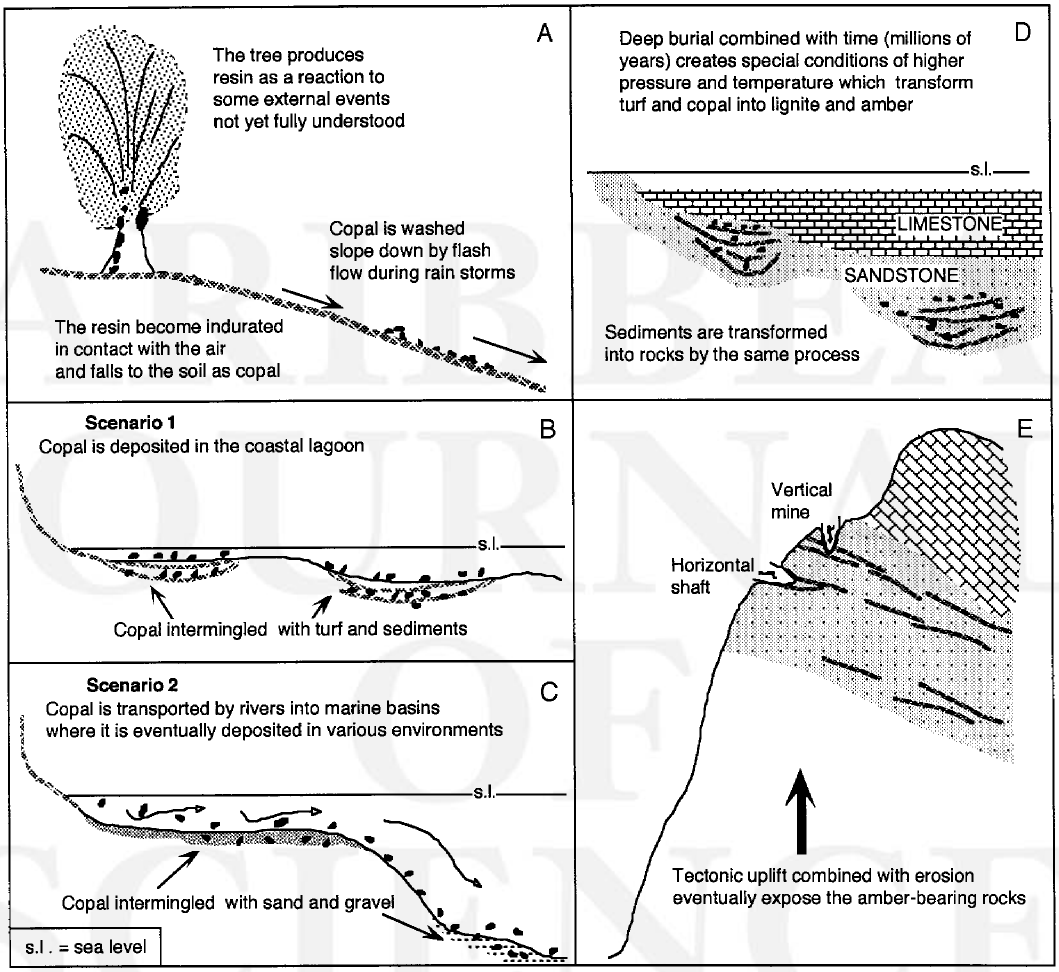

FIG. 10. Formation of the amber/lignitic deposits in the Comatillo basin, Dominican Republic.

It is generally accepted that the production of resin by *H. courbaril* is the result of mechanical and/or biotic wounds because resin protects against infection (Langenheim, 1990; Grimaldi, 1996). However, during 1996 and 1997 the author observed in the Dominican Republic several *H. courbaril* trees that naturally exude very small amounts of resin (also noted by Wu, 1997). Resin was not produced when branches were artificially broken or when the cortex was damaged. The author observed no resin production by *H. courbaril* during November 1998, several weeks after Hurricane Georges severely damaged many trees in the Dominican Republic The only place where *H. courbaril* contained resin was under the bark, in places where termites, ants, and other insects built their nests. Unexpectedly, the resin was clear and contained no trapped animals. Botanists working with species of *Hymenaea* in Peru and Bolivia have not noticed massive exudates of resin (Robin Foster, pers. comm.).

According to Sergio Leiva, an old amber miner and nature observer from El Valle, Dominican Republic, *H. courbaril* produces small amounts of resin about two weeks after its cortex is damaged. He indicates that large amounts of resin are produced only if the tree is struck by lighting. Sergio showed the author that digging deeply around the trunk of an old *H. courbaril* copal may be found, sometimes in large amounts and with biotic inclusions. It is well known in the Dominican Republic that copal is sometimes collected and sold as amber.

Brouwer and Brouwer (1982) considered that forest fires can force trees to produce larger amounts of resin. High temperature produced by fire could work as efficiently as lighting, but significant amounts of ash or burned animals and plants have not been reported in Dominican amber.

The *climate-geography factor* is related to the position of the *Hymenaea*-rich forest on the northern slope of the Hispaniolan highlands, south of the Comatillo lagoonal-marine basin (Fig. 9). Today, a humid rain forest (more than 2000 mm/year rainfall) exists on the northern slopes of the Greater Antilles because winds bring moisture that produces rainfall. The northern slope of the Miocene mountains probably received much rainfall and the forest was frequently exposed to rainstorms and thunderstorms. The high relative humidity would have enhanced bacterial, fungal and insect attacks on the trees (Langenheim, 1990), while the action of the wind produced mechanical damage.

The hydrodynamic factor is related to the rapid burial of the copal. This was very important because weather destroys exposed copal. Frequent rains washed the organic-rich soil of the forest and transported copal down-slope. In the Comatillo basin, organic litter was efficiently transported and deposited in the lower reaches of the slope, at the lagoonal and coastal areas, creating a growing bed of turf (peat) intercalated with organic-rich clays containing large amounts of copal. This process was favored by the fact that the *Hymenaea*-rich forest faced a well-protected marine enbayment (Figs. 8, 9). At least three main deposition environments were present in this basin: lagoonal, deltaic, and deep marine.

In river and lagoons, resin and copal will float in fast moving water but sink as soon as the current is negligible (Fig. 10: B). In the sea, some copal will float and disperse in high energy environments and some will sink. Sinking may be enhanced by high-density material adhered to the copal, such as soil and decayed wood, and by the occurrence of density flows which carry the copal mixed with mud (Fig. 10: C). The occurrence of isolated fragments of amber in well-documented turbidites has been reported (García and Harms, 1988; Harms, 1990), so it is likely that copal can sink into deep-water deposits. Theoretically, a high-energy, heavy mudflow can carry large amounts of copal down-slope if they are well-incorporated in the high density mud. When the mud flow reached the seafloor and spread laterally in layers a few centimeters thick, the copal probably concentrated along with the sand. The occurrence of thin beds of lignite within this deep-water section is probably due to secondary accumulation of the lighter vegetal debris embedded in water and carried into the sea by the density flow.

The Yanigua Formation represents the depositional scenario in the low-energy lagoon and coastal swamp environments. The reduced amount of rock detritus in Yanigua clearly indicates that erosion in the forest facing the lagoon was not very extensive, and that the soil and organic litter were mostly removed during rainstorms. Some isolated turbulent flows that deposited lenticular beds of gravel within the clay are so limited in area and scale, that they probably represent the action of local high energy water conducts, such as local creeks.

The amber deposited in the scenario of deltaic and open marine environments (La Toca Formation) followed a different process (Fig. 10: C). The rivers that cut across the Cordillera Central carried large amounts of silt, sand, and gravel that became intermingled with the slope-wash organic-rich input. As is common for sediment-rich rivers, large deltaic-fan deposits probably developed in the siliciclastic ramp facing the marine basin (Fig. 9). The copal-bearing alluvium was deposited in the river delta, mostly along the low-energy environments of the interchannel flat. Frequent sinking of plant debris probably concentrated as turf layers which diagenesis transformed into lignite. As is normal in deltas, contemporaneous erosion of already deposited beds will carry fragments of turf (future lignite) and copal (future amber) into deeper areas of deposition in the basin sea floor (Fig. 10: C). Therefore, in the sedimentary basin the hydrodynamic factor was responsible for rapid burial and resedimentation (recycling) of the copal in the different depositional environments. This guarantees that the copal was additionally protected from the action of erosion and surface biodegradation, which is the first and most important requisite for fossilization.

Amber is usually found as local concentrations in particular horizons (Brouwer and Brouwer, 1982; Redmond, 1982; Eberle et al., 1982). This implies that the factor controlling the concentration of copal fragments operates during sedimentation-a combination of paleo-relief and transport. In the lagoonal and coastal swamp environments, where slope-wash caused by rain is the main way of transporting copal to the basin, it can be suggested that the paleo-relief of the basin floor and source areas determined the areas of accumulation and dispersion. Where a mountain ridge faced the basin, little copal accumulated in front of the ridge, whereas increased accumulation took place in places where a local amphitheater faced the basin. The irregularities of the water table in the lagoon and coastal swamps created additional local barriers where more copal accumulated; this was probably most important in the deltaic flat, where slow-moving waters or local sandy bars and vegetal barriers probably enhanced the accumulation of organic-rich material, including copal. The way copal was concentrated in deep-water sediments in the La Toca Formation can also result from secondary concentration due to density segregation within the mud, and the shape and extension of the turbiditic lobes.

Diagenesis was another key factor in the formation of amber (Fig. 10:D). Diagenesis includes the chemical and physical modifications that occurred in the sediments after deposition. Autigenic pyrite is found in the lagoonal deposits of the Yanigua Formation, suggesting that diagenesis took place in an anoxic, sulfur-rich environment (Brouwer and Brouwer, 1982). In the Yanigua Formation, the lignitic beds are thick, very hard, brittle, and the intercalated clays and silts have gone through compaction strong enough to break and flatten mollusk shells. This phenomenon was produced by confined pressure due to deep burial of the copal-bearing sediments, probably up to one kilometer below the earth's surface, since the Yanigua Formation is covered by a few hundred meters of limestone (Los Haitises Formation). This event, which lasted several million years, placed the sedimentary pile under conditions of increased temperature and pressure, ultimately producing sediment compaction, diagenesis, and lithification. In the La Toca Formation, diagenesis also took place in anoxic conditions, as demonstrated by the dark color of the organic-rich amberiferous beds. As in the previous example, the sediments were deeply buried, more than one kilometer below earth's surface, during several millions of years. Copal matured under this condition until it became amber.

Still, it is a puzzle why the Maissade and Cibao Formations do not contain large accumulations of amber, since they have the same lithology and age as the Yanigua Formation (Fig. 2). Another puzzle is why amber is unknown from Cuba and South America, where *Hymenaea* trees are common today. No less problematic is the rare occurrence of small amounts of amber in the Sombrerito Formation of south central Hispaniola (García and Harms, 1988). The explanation is probably related to some missing factor among those previously listed for the amber-bearing region of northern Hispaniola. For example, it is evident in the paleogeographic map (Fig. 8) that the Comatillo basin was surrounded by a large slope forest, providing more area for the development of the *Hymenaea protera* forest. Land areas near the Plateau Central-San Juán basin of Hispaniola and the Las Tunas basin of Cuba were probably smaller. Perhaps *H. protera* was not widely distributed in the Greater Antilles, or maybe the tree was more abundant in the northern slope of paleo-Hispaniola due to particularly favorable conditions of altitude and humidity.

A secondary factor that may be involved

is modern topography (Fig. 10: E). For example, the dissected mountain ranges efficiently expose the amber-bearing deposits, in such a way that many years ago amber was even mined along rivers. The Maissade and Los Arabos Formations outcrop in areas of less dissected relief, and natural exposures are sparse and heavily weathered. Geological exploration is required before a final conclusion can be reached about the amber prospect of these formations. Nevertheless, the Sombrerito (south central Hispaniola), San Sebastián, and Cibao Formations (Puerto Rico) are well exposed in deeply dissected areas, but only small isolated fragments of amber have been reported (García and Harms, 1988; Iturralde-Vinent and Hartstein, 1998).

In conclusion, the origin of the unusually large Miocene deposits of amber in Dominican Republic remain a puzzle, but can probably be explained as the fortunate combination of:

i) Adequate conditions of relief and soil for the development of a large local population of resin-producing trees;
ii) Abundant occurrence of *Hymenaea protera*, with peculiar characteristics for the production of resin;
iii) A timely constrained warm and humid climatic optimum nearly 16 m.y. ago, which enhanced the production of resin, maybe as a consequence of larger populations of tree-dwelling bacteria, insects and fungi, but especially due to frequent thunderstorms;
iv) Special conditions for the rapid deposition of copal in marine basins located near the source;
v) Adequate environment of diagenesis due to deep burial of copal and turf bearing sediments.

Acknowledgements.—I thank Ross MacPhee and David Grimaldi (American Museum of Natural History, N.Y.), Salvador Brouwer (Sociedad Dominicana de Geólogos, D.R.), Iván Tabares (Dirección General de Minería, D.R.), Victor González (San Juán, Puerto Rico), Jake Brodzinski (Santo Domingo, D.R.), Jorge Caridad (Museo Mundo de Ambar, D.R.), Dyoris Perez (Museo Nacional de Historia Natural, D.R.), and José A. Ottenwalder (Oficina PNUD, D.R.) for assistance during field work. Consuelo Díaz and Rafaela Perez (Instituto de Geología y Paleontología, La Habana), Gena Fernández (New York Botanical Garden, N.Y.), W.A. van den Bold (Holland), Paula M. Mikkelsen (American Museum of Natural History, N.Y.), and Timothy Bralower (University of North Carolina at Chapel Hill) identified the fossils from the samples collected by the author. Grenville Draper (Florida International University) kindly provided unpublished data about the occurrence of amber in Jamaica. Grenville Draper, R. A. Davis, Jr. (University of Southern Florida), and Robin Foster (Field Museum of Natural History, Chicago) reviewed the manuscript and made many useful suggestions. This work was supported by grants from the Office of Grant and Fellowships of the American Museum of Natural History, the former RARE Center for Tropical Conservation, and the National Geographic Society (6009-97).

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