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Late Cretaceous–early Tertiary paleomagnetic data and a revised tectonostratigraphic subdivision of Costa Rica and western Panama

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ABSTRACT

New paleomagnetic data are presented in the context of a revised tectonostratigraphic subdivision of the Mesozoic-Tertiary oceanic basement of Costa Rica. We present the tectonostratigraphic characteristics and areal extent of four terranes (Chorotega, Nicoya, Golfito, and Burica) bordered toward the Middle America Trench by the Tertiary Osa-Caño Accretionary Complex. The paleomagnetic data are derived from Upper Cretaceous and Paleocene pelagic limestones.

The Chorotega Terrane constitutes most of the southern Middle American Landbridge and was the western edge of the Caribbean plate during the Late Cretaceous–Paleocene. The Nicoya Terrane comprises the Santa Elena Peninsula and most of the outer Nicoya Peninsula. The Nicoya Terrane includes the Nicoya Complex *(sensu stricto)* and should therefore probably be regarded as a composite terrane. The Golfito Terrane forms the Golfito region and extends into Panama to the Azuero Peninsula. The Late Cretaceous basement of the terrane is thought to have formed a marginal piece of the Caribbean oceanic plateau, transported northward by strike slip along the rim of the Caribbean plate. The Burica Terrane forms the Burica Peninsula. The terrane is thought to represent an accreted, structurally high piece of a primitive island arc. The inner Osa Peninsula is formed by a thick pile of oceanic basalts including Late Cretaceous to Eocene sediments. The outer Osa Peninsula and the Caño Island are built by the Osa-Caño Accretionary Complex, a mélange-type complex characterized by strongly deformed turbidites and hemipelagic and pelagic sediments that range in age from Late Cretaceous to Miocene. The exotic terranes are thought to have originated outboard in the Paleopacific, been brought into contact with the Caribbean plate boundary by plate convergence, and then been moved farther north by strike-slip motion along the margin.

The paleomagnetic data for the Chorotega Terrane indicate an origin close to its present latitude and no significant rotation relative to South America since Late Cretaceous time. The paleomagnetic data obtained from the Nicoya Terrane imply a low southerly Late Cretaceous paleolatitude and almost no rotation relative to the Chorotega Terrane. The Nicoya Terrane was about 16° of latitude south relative to

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the Chorotega Terrane in Late Cretaceous times. The paleomagnetic data from the Golfito Terrane indicate a Late Cretaceous equatorial paleolatitude and counterclockwise rotation of about 60° relative to the Chorotega Terrane. Similar paleomagnetic data were obtained from the Azuero Peninsula in southwestern Panama. The paleomagnetic data from the Burica Terrane indicate a low northerly latitude in the Paleocene and a counterclockwise rotation of nearly 90° relative to the Chorotega Terrane.

INTRODUCTION

Oceanic basement rocks and associated sediments crop out along the Pacific Coast of Costa Rica, Panama, and northwestern Colombia. The Santa Elena and Nicoya Peninsulas, in northwestern Costa Rica, are the most extensively studied parts of this coastal outcrop. In the Nicoya Peninsula, Dengo (1962) defined the Nicoya Complex as a pre-Senonian tectonized body of basaltic basement, associated with oceanic sediments and unconformably overlain by Upper Cretaceous deep-water sediments. A refined analysis and definition of the Nicoya Complex was provided by Kuijpers (1980), who was the first to recognize nappe structures in the Nicoya Complex. Bourgois et al. (1984) and Azéma et al. (1985) documented the emplacement history and established the tectonic relationship between the Nicoya Complex, composed of the Esperanza and Matapalo units, and the overriding Santa Elena Ultramafic Unit. Ages ranging from late Liassic to Santonian have been documented for parts of the Nicoya Complex (Schmidt-Effing, 1979; Baumgartner, 1984; de Wever et al., 1985).

Many authors have included the bulk of the basaltic basement and associated oceanic sediments outcropping in Costa Rica and Panama with the Nicoya Complex (Henningsen and West, 1967; Pichler and Weyl, 1973; Schmidt-Effing, 1979; Berrangé and Thorpe, 1988; Bowland and Rosencrantz, 1988; Escalante, 1990; Frisch et al., 1992). However, it has been recognized that there are fundamental differences in age, lithology, tectonic structure, geochemical characteristics, and paleomagnetic signature in different areas (Wildberg, 1984; Baumgartner, 1984; Baumgartner et al., 1984; Baumgartner, 1987; Frisch et al., 1992). Baumgartner (1987) considered the basaltic basement south of the Nicoya Peninsula as independent units distinct from the Nicoya Complex (*sensu stricto*). Baumgartner et al. (1989) and Baumgartner (1990) subdivided the Costa Rican Pacific coast into three tectonostratigraphic suspect terranes (Nicoya Complex, Golfito and Burica Terranes) and defined the Caño Accretionary Complex (an accretionary mélange) formed as a result of Tertiary accretion in the Middle America Trench.

Few paleomagnetic surveys have been undertaken in Costa Rica. De Boer (1979) discussed two mean paleomagnetic directions obtained from igneous rocks on the Nicoya Peninsula. These data are not assigned to a precise location and are therefore of no use in further studies. The first useful data are given by Gose (1983), who initiated comprehensive paleomagnetic studies in Costa Rica and Nicaragua. According to these data, the Nicaraguan sites have been close to their present latitude since the Cretaceous, whereas the Costa Rican sites show a Southern Hemisphere origin. Gose's (1983) sites are included in our dataset, although sites 5 and 6 are excluded because of probable remagnetization and poor within-site precision, respectively. Frisch et al. (1992) presented geochemical and paleomagnetic data from Costa Rica and western Panama (see also Sick, 1989). Their results imply a broadly defined equatorial origin for the whole region, with variable amounts of local block rotation.

This chapter presents a synthesis of an on-going study of the tectonostratigraphic subdivision of Costa Rica and western Panama being carried out by P. O. Baumgartner and associates. The Costa Rican isthmus is subdivided into four tectonostratigraphic terranes and the Osa-Caño Accretionary Complex (Fig. 1) (Di Marco, 1994). The tectonostratigraphic characteristics of these units are described. We also present paleomagnetic data and discuss the degree of allochthony of the tectonostratigraphic units with respect to the Caribbean plate.

TECTONOSTRATIGRAPHIC SUBDIVISION

Introduction

The Mesozoic and early Tertiary oceanic basement and associated deep-water sediments of Costa Rica and Panama continue to be included with the Nicoya Complex. Over 30 years ago, Dengo (1962) expressed doubts as to whether basaltic basement complexes outcropping in southern Costa Rica should be included with the Nicoya Complex, principally because of the absence of the pre-Campanian deformational phase characteristic of the Nicoya Complex (*sensu stricto*). Baumgartner et al. (1984) documented fundamental differences in magmatism, sedimentary environment, age, and tectonic history between units of the northern and the southern Pacific coast of Costa Rica (see also Baumgartner, 1987; Seyfried et al., 1991).

We propose a revised subdivision of the Costa Rican basement and overlying Mesozoic–early Tertiary sediments into several tectonostratigraphic units, each of which is characterized by a distinct tectono-sedimentary history. This subdivision (Fig. 1) is based on the detailed stratigraphic work carried out in the last 12 years by members of the Escuela Centroamericana de Geologia, by various foreign research groups, and by the authors. Our own fieldwork in the last few

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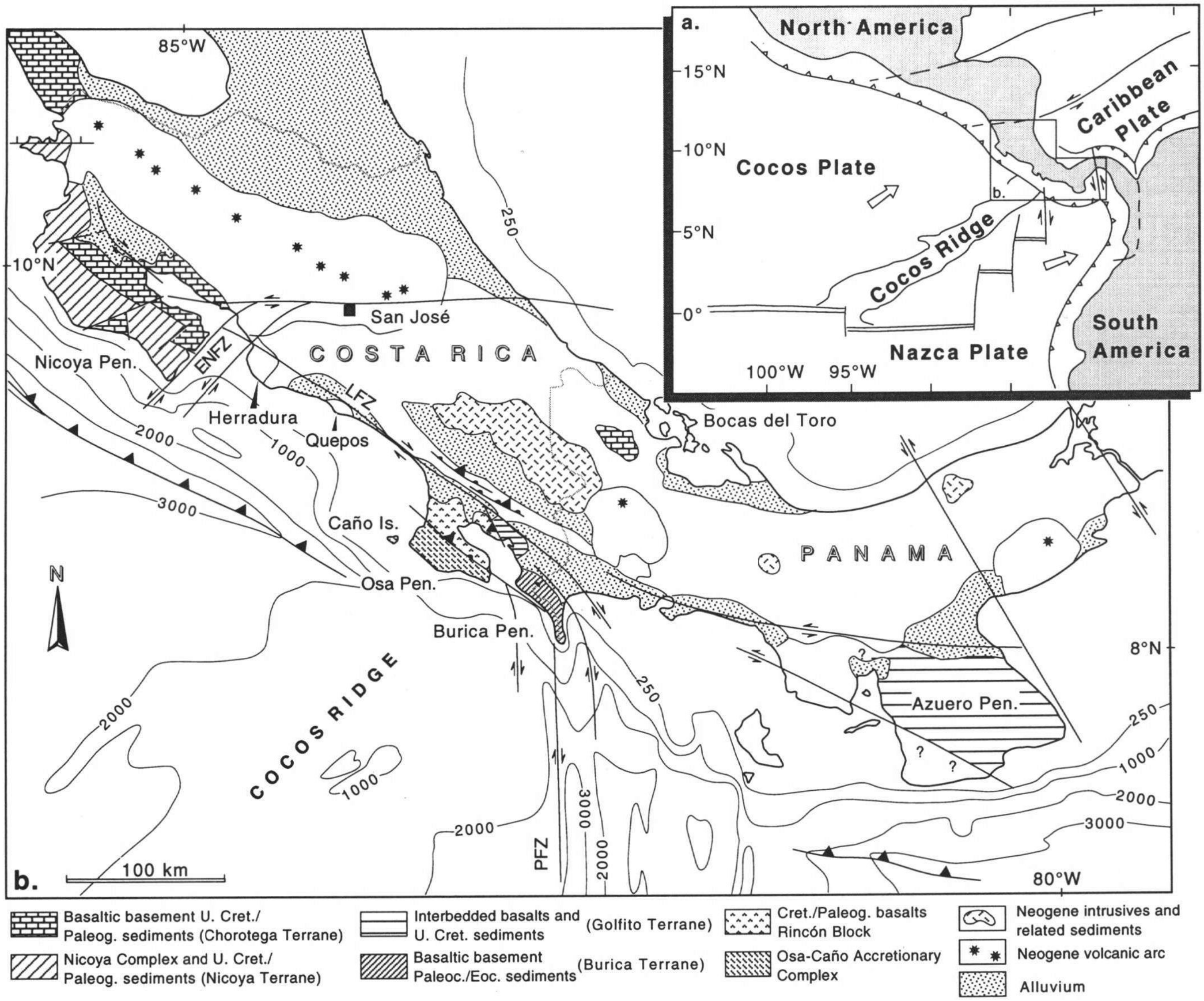

Figure 1. a, tectonic setting of Central America. Modified from Case and Holcombe (1980). b, geological map showing the main tectonic features and distribution of the tectonostratigraphic terranes of Costa Rica and western Panama (overlap sequences have been removed). ENFZ = East Nicoya Fracture Zone. LFZ = Longitudinal Fault Zone. PFZ = Panama Fracture Zone.

years has been focused on the southern Pacific area (Quepos, Osa, Golfito, Burica). Results of this work will be reported in detail in future publications (see Di Marco, 1994). This chapter summarizes the igneous and sedimentary characteristics leading to the proposed tectono-stratigraphic subdivision and documents important stratigraphic events in each area that constrain emplacement and accretion history.

We adopt the terrane nomenclature (Howell et al., 1985) because the outcrops along the Pacific coast of Costa Rica reveal a number of fault-bounded basement blocks, each of which is covered by a more or less unique stratigraphic sequence. Except for the outer Osa Peninsula and parts of the Nicoya Complex (*sensu stricto*), the Costa Rican Pacific coast can be regarded as a collage of stratigraphic terranes that represent fragments of ocean basins, oceanic seamounts, and/or island arcs. The Osa-Caño Accretionary Complex outcropping in the outer Osa Peninsula should be regarded as a disrupted terrane (Howell et al., 1985) that includes blocks of ophiolitic rocks but shows no evidence of an igneous basement (see below).

Many authors have attempted to organize the sedimentary basins of northern Costa Rica into a single paleogeography (Dengo, 1962; Lundberg, 1982; Baumgartner et al., 1984; Seyfried and Sprechmann, 1985; Seyfried et al., 1991). Although the sequences in the Tempisque area and southern Nicaragua show common features (Sprechmann et al., 1987; Winsemann,

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1992), correlation between this "inner forearc" and the "outer forearc" in the outer Nicoya Peninsula is difficult. These areas are separated by a number of faults, and where the sedimentary cover on the basaltic basement is preserved, completely different sedimentary sequences are juxtaposed along these faults (see below). The igneous and sedimentary sequences recorded in the Burica, Osa, and Golfito areas have little in common with each other and even less in common with those of northern Costa Rica. These areas are separated from each other by major faults or fault zones and are designated as terranes (see Howell et al., 1985). In most cases, these fault zones do not represent the original suture that resulted from the accretion of the terrane but are Neogene to Recent (active) faults. The present-day juxtaposition of terranes is the result of a multiphase emplacement, involving both initial plate convergence and successive phases of strike-slip motion. Amalgamation and accretion of terranes can be documented by local and regional sedimentary and tectonic events such as the onset of coarse-clastic sediments and deformational phases. The exotic terranes are thought to have originated somewhat outboard in the Paleopacific, been brought into contact with the Caribbean plate boundary by plate convergence, and then been moved farther north by strike-slip motion along the margin. The collage of terranes is bordered toward the Middle America Trench by the Tertiary Osa-Caño Accretionary Complex.

Areal extent and boundaries of terranes

The Chorotega Terrane constitutes most of the southern Middle American Landbridge. It includes the southern Nicaragua (Rivas) Basin and the Tempisque Basin, including the inner part of the Nicoya Peninsula (Fig. 2). It is the original basement of the Neogene to Recent volcanic arc and extends into Panama at least as far as the Bocas del Toro area (Fig. 1), where late Campanian and younger sediments crop out in the Changuinola River. The Chorotega Terrane was the western edge of the Caribbean plate during the Late Cretaceous–Paleocene. The other terranes proposed in this chapter are allochthonous relative to the Chorotega Terrane.

The boundary between the Chorotega and the Nicoya Terranes is at present poorly understood and is therefore drawn somewhat tentatively. The boundary is represented by northeast-southwest–trending faults (Figs. 2 and 3) that probably had an important strike-slip component. These faults are offset in the southern part of the Nicoya Peninsula by younger southwest-northeast–trending strike-slip faults that could be related to the East Nicoya Fracture Zone (ENFZ) (Corrigan et al., 1990), which trends perpendicular to the mainland coast in the southeastern part of the Nicoya Peninsula (see Baumgartner et al., 1984; Burbach et al., 1984) (Fig. 1). Multiphase faulting has caused the area of Puerto Carrillo (Fig. 2) to become tectonically isolated from the main Chorotega Terrane.

The Nicoya Terrane comprises the Santa Elena Peninsula and most of the outer Nicoya Peninsula facing the Pacific. The Nicoya Terrane includes the Nicoya Complex (*sensu stricto*) and should therefore probably be regarded as a composite terrane (Howell et al., 1985). South of the ENFZ, a heterogeneous collage of fault-bounded promontories and peninsulas borders the Chorotega Terrane. The Herradura promontory lies at the junction of the Longitudinal Fault Zone (LFZ) and the ENFZ and is affected by both fault systems (Fig. 1). This zone is tentatively included in the Chorotega Terrane and awaits more detailed analysis. The Quepos promontory (Fig. 1) is separated from the Chorotega Terrane by the LFZ and displays a unique sedimentary sequence (Baumgartner et al., 1984; Winsemann, 1992). The interpretation of the Quepos promontory as a separate terrane will be addressed elsewhere.

The Osa Peninsula, the Golfito Terrane, and the Burica Terrane are separated from each other by high-angle reversed faults that are either observed in the field (Fig. 4) or inferred from unpublished seismic data. These units are separated from the Chorotega Terrane by the LFZ. The Osa Peninsula comprises two fundamentally different units: (1) the Rincón Block, a tectonically thickened pile of basaltic basement with rare occurrences of Late Cretaceous to Eocene sediments, and (2) the Osa-Caño Accretionary Complex, a pile of accreted oceanic and trench-fill sediments including some ophiolitic blocks. The two units are separated by a trench-parallel high-angle reverse fault that is the trace of an earlier strike slip fault.

STRATIGRAPHY AND SEDIMENTARY EVOLUTION OF EACH TERRANE

Chorotega Terrane

Basement and associated Cretaceous-Paleocene sediments. The Chorotega basement comprises oceanic basalts of middle-Late Cretaceous or older age. Few data are available on their geochemistry, since most recent work has been focused on the outer Nicoya Peninsula (Nicoya Terrane). We believe, however, that this basement was part of the Caribbean seafloor, thickened by the Caribbean sill event (Burke et al., 1978). The oldest associated sediments range in age from Albian to Santonian and are likely interbedded in the volcanic rocks of the Caribbean sill event. These sediments are more than 600 m thick and include bituminous shales, siliceous mudstones, and tuffs in the Tempisque area (Azéma et al., 1979; Astorga, 1987). This facies association is unknown in the Nicoya Terrane, where relatively thin radiolarites prevail during the same time interval. Widespread basaltic breccias and conglomerates of Campanian age interfinger with or are overlain by Campanian deep-water sequences, and in the Bajo Tempisque area (Colorado, Fig. 2), deep-water breccias contain reworked shallow-water fossils (Rivier, 1983; Seyfried and Sprechmann, 1986; Winemann, 1992). In the area of Tambor-Paquera (Fig. 3), the basal breccias are more than 100 m thick and contain several-meter-sized blocks of radiolarite, basalt, and basaltic breccia (Punta Pochote, Playa Curú, Islas Tortugas). These

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coarse rockfall and debris-flow deposits document important post-Santonian erosion due to submarine relief. The late Campanian–early Maastrichtian is usually represented by more than 50 m of 0.5- to 1-m-thick beds of white micritic limestones rich in *Globotruncana* sp, radiolarians, with some fine-grained basaltic detritus (Bahía Murcielago, Río Changuinola). Interbeds of dark shale may occur. Although no shallow-water fossils were found in these sequences, we suspect the thick bedding to be the result of periplatform ooze input into a hemipelagic environment of sedimentation. Sediments of this unit contrast with the usually condensed Senonian sediments of the Nicoya Terrane. Arc-derived siliciclastic sedimentation prevailed in the Chorotega Terrane from late Maastrichtian probably until Paleocene–middle Eocene time. Up to 3,000 m of turbiditic forearc sequences were deposited in this time interval. In contrast, hemipelagic siliceous limestones were deposited during the upper Paleocene–middle Eocene in the Nicoya Terrane.

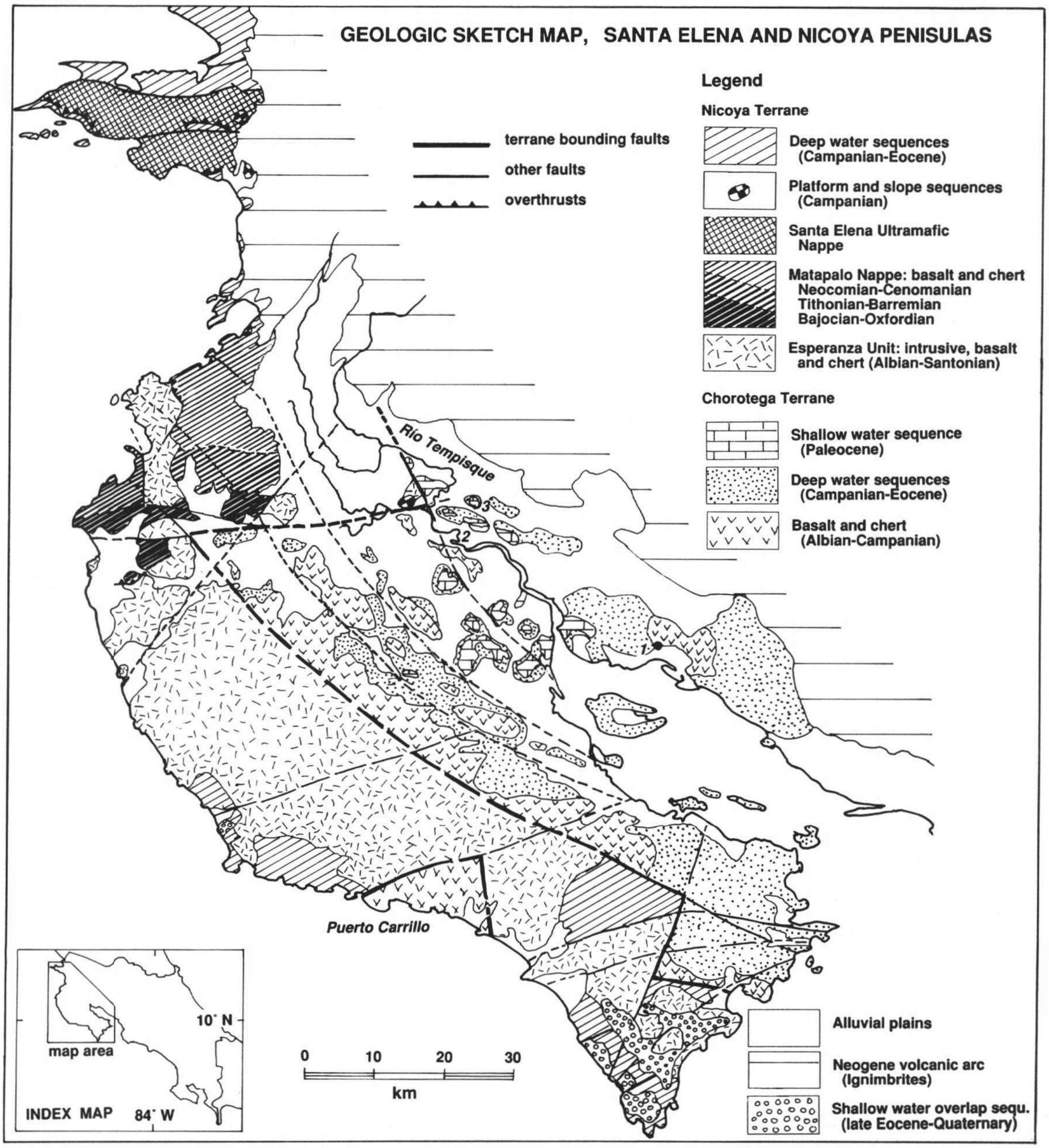

Figure 2. Map of the Santa Elena and Nicoya Peninsulas showing a tentative tectonostratigraphic subdivision. Data from Rivier (1983), Baumgartner (1984), Azéma et al. (1985), Arias and Denyer (1992a, b), Denyer and Arias (1992), Gursky (1988), and unpublished maps by P. Denyer, E. P. Kuijpers, and the authors. 1: Colorado; 2: Cerros Guayacán; 3: Cerro Espiritu Santo.

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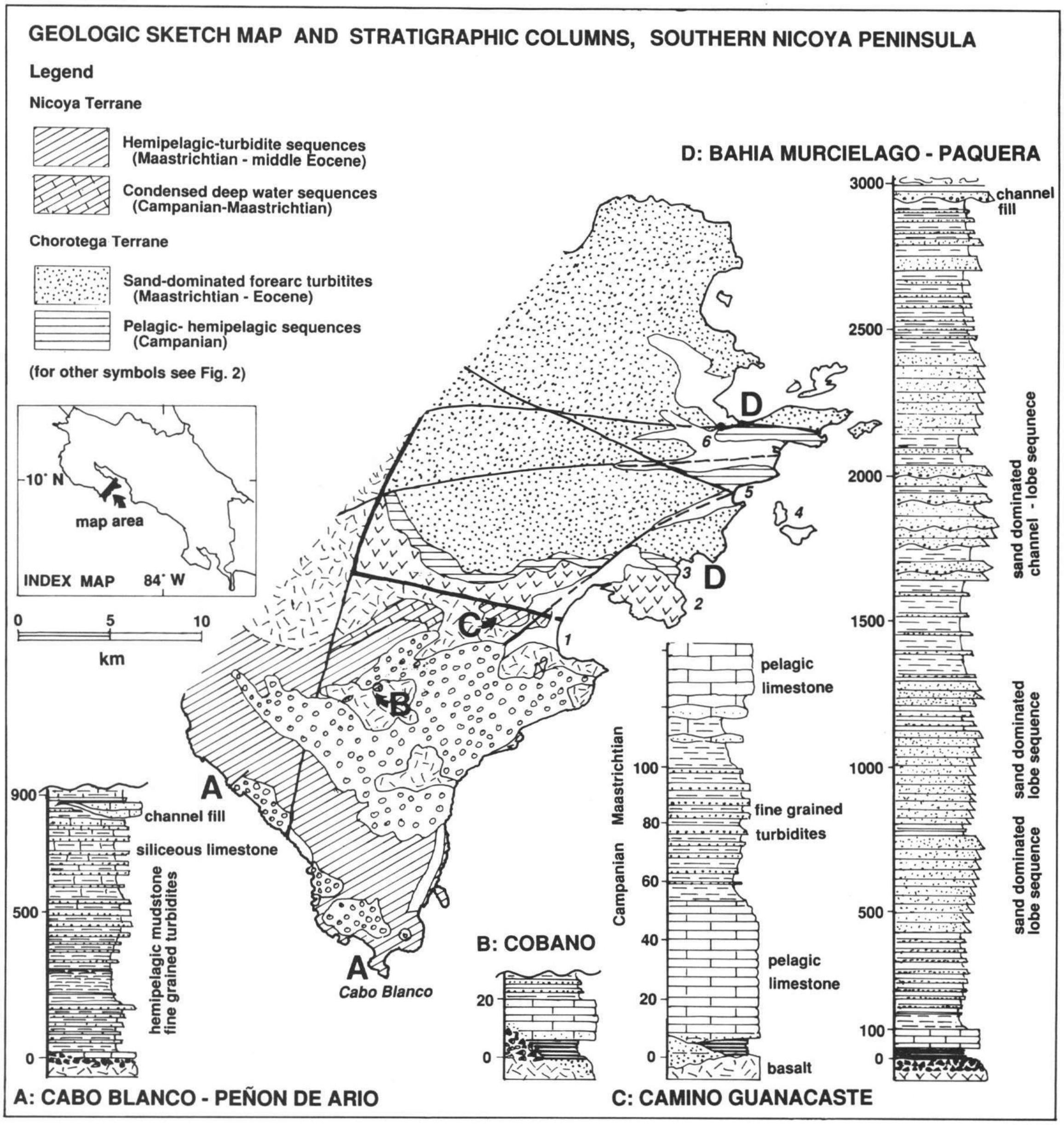

Figure 3. Geologic map and representative stratigraphic sections of the Southern Nicoya Peninsula: evidence for the boundary between the Chorotega and Nicoya Terranes. Data from Mora (1985), Baumgartner et al. (1984), Winsemann (1992), and unpublished data by the authors. 1: Tambor; 2: Punta Pochote; 3: Bahía Murcielago; 4: Islas Tortugas; 5: Playa Curú; 6: Paquera. Sections A to C are included in the Nicoya Terrane. Section D is included in the Chorotega Terrane. Note different scales of sections.

Barra Honda Platform. The Barra Honda limestones, micritic limestones of predominantly restricted platform origin (Mora, 1981), unconformably overlie Upper Cretaceous–Eocene deep-water sequences in the Tempisque area. Rivier (1983) suggested a middle Eocene or younger flooding of a slightly deformed area to explain the unconformable onset of deposition of these limestones. Sprechmann et al. (1987) correlated the Barra Honda limestones with the rudist-bearing limestones of Santa Elena (El Viejo Formation; Schmidt-Effing, 1975) on the basis of early Maastrichtian globotruncanids that they recovered from sheared mudstones below the base of the limestones. They also mentioned Campanian larger foraminifers recovered from unspecified limestones. Neither Sprechmann et al. (1987) nor Calvo (1987) provided exact sample locations or measured sections that would show how the reported Late Cretaceous fossils relate to the micritic Barra Honda facies, which is generally de-

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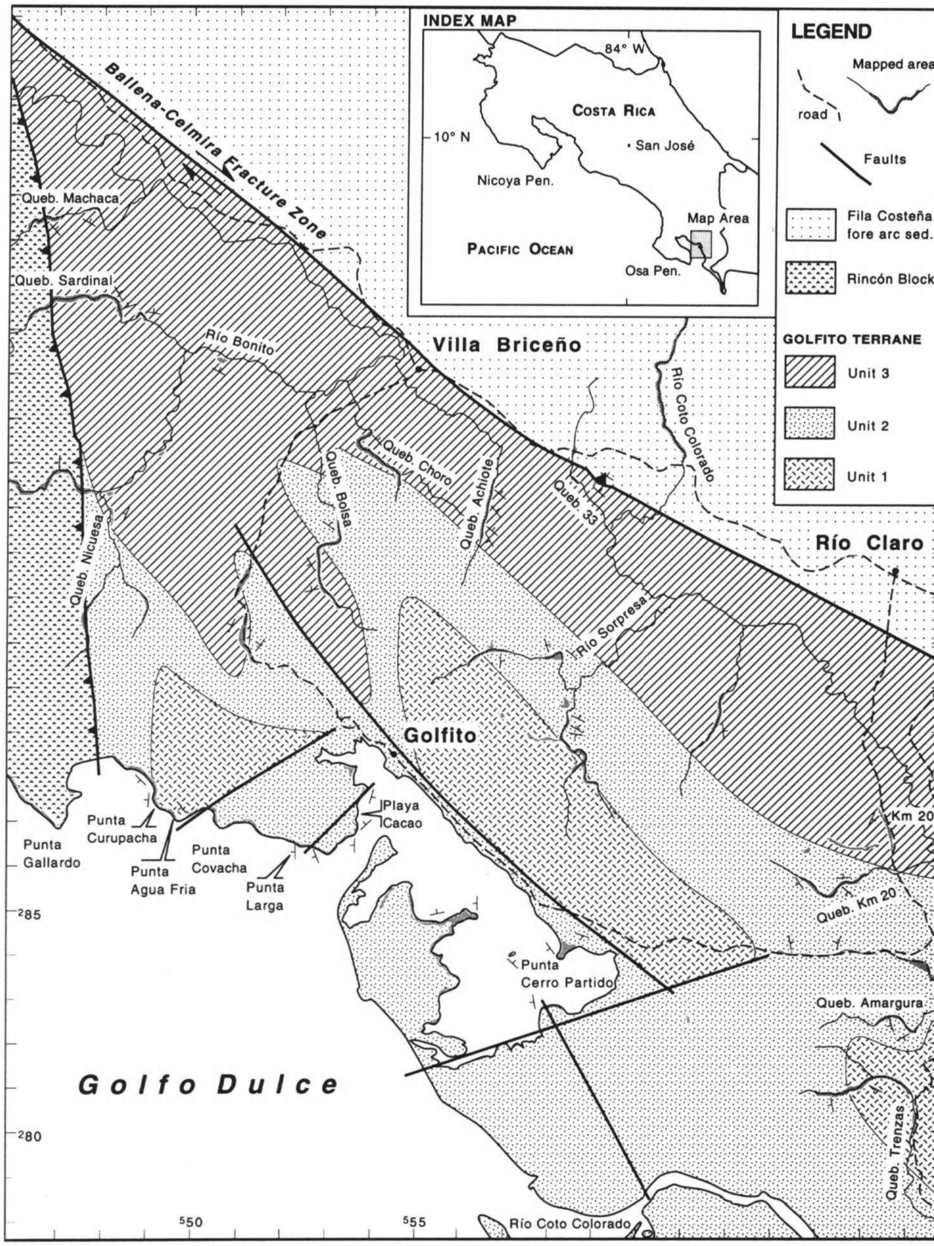

Figure 4. Interpretive geologic sketch map of the pre-Neogene geologic units of the Golfito Terrane. Mapped areas are shaded. Lithostratigraphic sections are shown in Figure 5.

void of age-diagnostic fossils. Late Cretaceous reworked shallow- and deep-water material is, however, quite common in the Paleocene-Eocene sequences that underlie the Barra Honda limestones (Seyfried and Sprechmann, 1985; Winsemann, 1992). The presence of reworked Campanian larger foraminifers and rudistids in Paleocene-Eocene mass flows demonstrates the erosion of Campanian carbonates produced in an open marine, high-energy environment that is distinct from the mud-dominated Barra Honda environment. Calvo (1987) assumed that the rudist-foraminifer facies is marginal to the restricted Barra Honda facies but provided no evidence of lateral continuity between the two formations. In view of the lack of precise stratigraphic data, we doubt this interpretation and consider that a late Cretaceous age of the Barra Honda limestones has not been established.

A number of observations are the basis of our interpretation of the Barra Honda limestones. The occurrence of the late Campanian rudist and larger foraminifer–bearing platform and slope facies (El Viejo Formation) is restricted to the Santa Elena and northwestern Nicoya Peninsula (Fig. 2) and is therefore a feature of the Nicoya Terrane. In the Bajo Tempisque area (Colorado, Fig. 2), rudistids and Campanian larger foraminifers are reworked into coarse ophioclastic deposits that

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directly overlie the basaltic basement (Barbudal Formation of Rivier, 1983; Seyfried and Sprechmann, 1985). These deposits probably formed during the late Campanian but do not contain clasts of Barra Honda–type carbonates. The first appearance of Barra Honda–type clasts in coarse mass-flow and channel-fill deposits associated with deep-water formations is systematically middle-late Paleocene in age (Sprechmann et al., 1987; Calvo, 1987; Winsemann, 1992). The Barra Honda–type micrites are therefore unlikely to be much older than middle-late Paleocene.

To the east of the Tempisque River, Barra Honda Limestones extend at least as far north as Cerros Guayacán (Fig. 2), where we found small *Discocyclina,* characteristic of a Paleocene-Eocene age, associated with the micritic facies. A few kilometers to the north, in the Cerro Espiritu Santo (Fig. 2), a more-than-50-m-thick sequence of platform limestones rich in upper Paleocene *Ranikothalia* rests with a well-exposed transgressive unconformity on siliceous pelagic mudstones (not on "Nicoya Complex" as illustrated by Calvo and Bolz, 1991). These mudstones, assignable to the Upper Cretaceous–Paleocene Sabana Grande Group (Dengo, 1962), have a thickness of about 100 m and rest unconformably on basalt. The transgression of the limestones is preceded by 5 m of reddish altered siliceous mudstones reminiscent of a paleosoil and by 4 m of carbonate conglomerate, including well-rounded and bored cobbles of Barra Honda–type algal micrites, rhodoliths, and *Ranikothalia*-bearing clasts, passing upward into bioclastic grain and packstones. To us, this sequence represents a marginal facies to the restricted Barra Honda platform. As a consequence, we conclude that this platform certainly existed during the late Paleocene and may have originated during the late early to middle Paleocene. Calvo and Bolz (1991) reported late Paleocene–early Eocene platform limestones from another locality of the Chorotega Terrane: Fila Chonta, about 20 km north of Quepos in the Fila Costeña.

Nicoya Terrane

Pre-Campanian units of the Santa Elena and Nicoya Peninsulas. The Nicoya Complex and the Santa Elena Ultramafic Unit are among the best-studied units in southern Central America. Nevertheless, the structural interpretation of these mafic and ultramafic units remains controversial. The presence of nappe structures was first proposed by Kuijpers (1980) for the Nicoya Peninsula and by Azéma and Tournon (1980) for the Santa Elena Peninsula. It was Kuijpers (1980) who interpreted the northeastern Nicoya Peninsula as a nappe structure, resulting from pre-Campanian compressive tectonics. Radiolarian biostratigraphic data confirmed these ideas, leading to the acceptance of a megastructure comprising the Santa Elena Ultramafic Unit and the northwestern Nicoya Peninsula (Bourgois et al., 1984; Azéma et al., 1985). Four units (Fig. 2) are recognized in this megastructure (see Baumgartner, 1987): (1) The Esperanza Unit can be considered as the relatively autochthonous unit forming the major part of the outcrops in the Nicoya Terrane. (2) The Matapalo Unit overlies the Esperanza Unit along a thrust contact. The Matapalo Unit is preserved as isolated klippes in the northwestern Nicoya Peninsula. (3) A volcano-sedimentary unit underlies the Santa Elena Unit in small outcrops and tectonic windows. (4) The Santa Elena Unit is the structurally highest unit in the nappe pile. Both in Santa Elena and Nicoya, there is clear evidence for compressive deformation with a southward vergence (Strebin, 1982; Azéma et al., 1985; Meschede et al., 1988).

The Matapalo Unit and the volcano-sedimentary unit of the Santa Elena Peninsula represent remnants of accretionary prisms that after their formation became emplaced on the Esperanza Unit and are overthrust by the Santa Elena Unit. The accretionary history preserved in these two units indicates Middle and Late Cretaceous subduction followed by Santonian–early Campanian obduction. The age distribution within the Matapalo Unit indicates a southward dip during its accretion. The predominantly primitive island arc origin postulated for the Esperanza Unit (Wildberg, 1984) may well be associated with this intraoceanic subduction, which probably began in pre-Albian times, although it is clearly documented only from the Cenomanian until late Santonian–early Campanian, when all units became obducted (Azéma et al., 1985). This obduction has again a southern vergence (Azéma et al., 1985; Meschede et al., 1988) and could well be related to relative motion along an intraoceanic transform fault system. The Middle America Trench system became established after this obduction and is independent of the pre-Campanian events described above.

Late Senonian–early Tertiary mesoautochthonous sequences. The late Santonian–early Campanian tectonic phase created an important (mostly submarine) relief that was subject to intense erosion. This relief produced marked facies changes in the late Senonian sedimentary cover. The basal unconformity that separates the highly deformed Nicoya Complex from the much less deformed late Senonian sedimentary cover is, however, only evident in the Santa Elena Peninsula and northwestern-central Nicoya Peninsula, where klippes of the Matapalo Unit are present and the deformation of the underlying Esperanza Unit is intense. The nappe front probably was never much farther south than the location indicated by the Matapalo klippes. In southwestern Nicoya Peninsula the late Senonian cover rests almost conformably on the basalts of the Esperanza Unit.

The structurally most elevated parts (Santa Elena Peninsula and northwestern Nicoya) reached into shallow waters and became partially subaerial. This is suggested by well-rounded boulder conglomerates that characterize the unconformity at the base of rudistid bioherms. In the remaining parts of the Nicoya Terrane, both rounded and angular boulder breccias are always associated with siliceous and/or calcareous pelagic sediments and suggest submarine relief, causing rockfall and debris flows in a deep-water environment during the Campanian-Maastrichtian.

Siliceous mudstones occasionally overlie the basal brec-

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cias and represent the oldest sediments of the sedimentary cover of the Nicoya Complex. Pelagic limestone sedimentation started everywhere in the late Campanian, both overlying the siliceous sequence described above as well as directly in contact with basalts or basaltic conglomerates. No intrusive contacts with Campanian limestones have been observed in the Nicoya Terrane. All contacts of sediments with basalts are cold, sedimentary contacts. In contrast with coeval facies of the Chorotega Terrane, the upper Campanian–lower Maastrichtian sediments are usually condensed and pelagic. During this time, sedimentation became more uniform over the entire Nicoya Terrane. Former neritic areas subsided to subphotic depths and sedimentation became pelagic. During the Maastrichtian, distal turbidites began to appear. Both in the Santa Elena and the Garza-Samara area, these early detrital facies are dominated by basaltic material and indicate local erosion rather than far-traveled turbidite systems.

Middle or upper Paleocene coarse channel-fill and overbank deposits (Winsemann, 1992), including boulders of andesites and platform limestones, indicate the initial juxtaposition of the Nicoya Terrane with the Chorotega island arc. These deposits may be indicative of the amalgamation of the two terranes. The source area for these beach-derived andesites and platform limestone boulders may have been farther to the southeast, owing to Paleocene-Eocene strike-slip motion of the Nicoya Terrane after initial amalgamation.

Golfito Terrane

The Golfito Terrane crops out along the northeastern shores of the Golfo Dulce (Fig. 4) and apparently extends into Panama to the Azuero Peninsula. The terrane is characterized by oceanic basalts and dolerites and by stratigraphically overlying Campanian-Maastrictian pelagic limestones, argillites, basaltic turbidites, and tuffs. In contrast to the Chorotega Terrane, no thick Maastrichtian-Paleogene sand-dominated forearc sequences exist. Except for the youngest (late Maastrichtian–Paleocene ?) sediments, which contain more acidic volcanic glass, the volcaniclastic material appears to be derived from local basaltic basement. Pelagic sediments are interbedded with volcanic breccias and flows and crosscut by dikes, indicating basaltic igneous activity until the middle Maastrichtian.

Detailed mapping allowed us to define a three-fold subdivision of the volcano-sedimentary sequences observed in the Golfito Terrane (Di Marco, 1994): (1) the basement composed of dolerites and basalts, (2) a sequence of interbedded volcanic flows and hemipelagic sediments, and (3) a sequence of volcaniclastic sediments (Fig. 5).

The basement (Unit 1). The central part of the Golfito region is floored by massive dolerites and oceanic basalts (Fig. 4). The minimum age of this unit can be determined as latest Campanian, based on planktonic foraminifers recovered from the base of the stratigraphically overlying sediments.

Interbedded volcanic flows and sediments (Unit 2). A suite of pelagic limestones bearing planktonic foraminifers and radiolarians, calcareous to siliceous mudstones, volcanic siltstones and sandstones, and basaltic breccia (Fig. 5) rests with a stratigraphic contact on the basement. This very variable sequence is intruded by basaltic dikes and sills and intercalated with basaltic flow units. Pelagic limestones from Unit 2 generally include Maastrichtian *sensu largo* foraminiferal assemblages. At Río Sorpresa (Fig. 4), a section of sedimentary rocks with thickness greater than 50 m contains several massive doleritic/basaltic flows (Fig. 5). In Quebrada Chorro, a middle Maastrichtian age was determined in pelagic limestones stratigraphically overlying a massive volcanic flow. Intermittent basaltic volcanic activity occurred during hemipelagic/pelagic sedimentation since the Campanian-Maastrichtian and lasted at least until the middle Maastrichtian.

The volcaniclastic sequence (Unit 3). Unit 3, characterized by the absence of volcanic flows and by the occurrence of coarse breccias and boulder beds, is well exposed in the northern and northeastern parts of the Golfito Terrane (Fig. 4). In the Quebrada Chorro and Quebrada Bolsa (Fig. 5), we observed olistostromes with blocks measuring up to several meters in diameter composed of pelagic limestone, basalt, and siliceous mudstone set in a volcaniclastic matrix. Some of the blocks were included in the matrix as semilithified blocks. These coarse-clastic rocks are locally (Quebrada Bolsa, Quebrada Nicuesa, and on the Golfito–Villa Briceño road, Figs. 4 and 5) capped by an unconformable sequence of fine-grained, massive green siliceous volcanic tuffs and tuffites. The presence of acidic volcanic glass shards suggests influence of an explosive volcanism. These rocks may be considered as an overlap sequence. Unit 3 is only dated at its base as middle Maastrichtian (Fig. 5); its top could range into the Paleocene.

The coarse clastic sediments with olistostromes clearly record a tectonic event that could be related to the initial collision of the Golfito Terrane with the Chorotega margin. This event is actually poorly dated. It must have happened after the cessation of middle Maastrichtian basaltic submarine volcanism, probably during the Paleocene. Arc-derived volcanic detritus is not present in the above-mentioned overlap sequence, as is the case for the Tertiary sediments of the Chorotega Terrane. We speculate that the Golfito Terrane, once in contact with the Chorotega margin, became an elevated area that was bypassed by arc-derived clastics. The stratigraphic sequence recorded in the Golfito terrane—mainly Unit 2 with its basalt flows interbedded with Late Cretaceous volcaniclastic and pelagic sediments—is typical of that from oceanic plateaus of Cretaceous age in the western Pacific (Bowland and Rosencrantz, 1988). Therefore, the terrane is thought to have formed a marginal piece of the Caribbean oceanic plateau, transported northward by strike slip along the rim of the Caribbean plate.

The Osa-Caño Accretionary Complex

Detailed mapping of coastal and river outcrops in the Osa Peninsula revealed two fundamentally different units. In the Osa isthmus and the inner Osa Peninsula (Fig. 6), a thick pile of oce-

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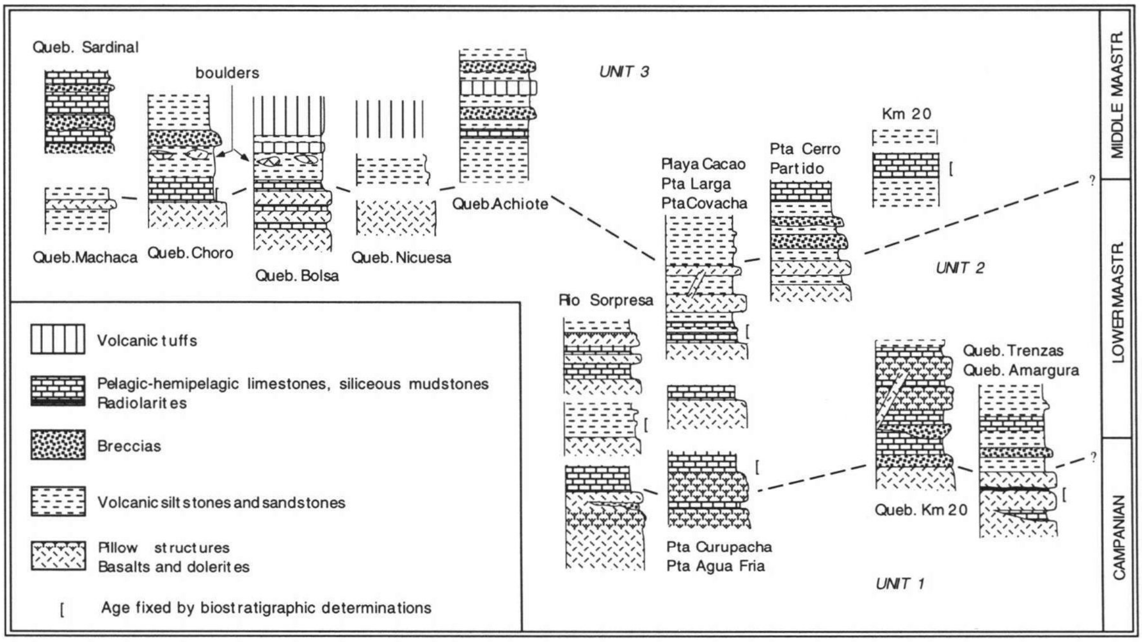

Figure 5. Lithostratigraphic sections in the Golfito Terrane (for localities see Fig. 4).

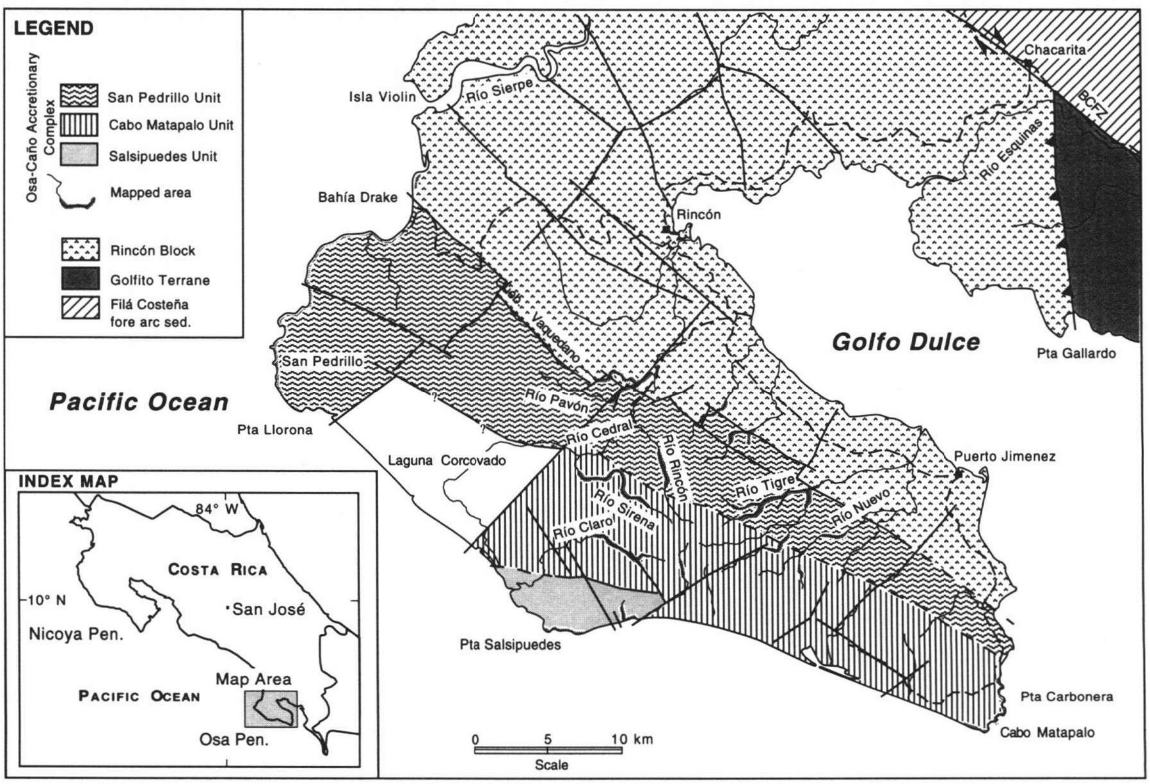

Figure 6. Interpretive sketch of the pre-Neogene geology of the Osa Peninsula. Mapped areas are shaded. BCFZ = Ballena-Celmira Fracture Zone (Corrigan et al., 1990). Note that the BCFZ is part of the LFZ (Longitudinal Fault Zone).

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anic basalts, including small amounts of sediments of Late Cretaceous to Eocene age, crops out. We refer to this unit as the Rincón Block (Fig. 6). This unit is dealt with in more detail by Di Marco (1994). The outer Osa Peninsula and the Caño Island are built by the Osa-Caño Accretionary Complex characterized by strongly deformed turbidites and hemipelagic and pelagic sediments (over 95% of volume) that range in age from Late Cretaceous to Miocene. In some places (San Pedrillo–Marenco) 10- to 100-m-sized blocks of oceanic basalt, dolerite, and minor amounts of gabbro and acidic cumulates occur in a hemipelagic sedimentary matrix. In contrast to published work on this area, we cannot confirm the existence of any basement underlying sediments in the outer Osa Peninsula.

The Osa-Caño Accretionary Complex forms the most external geological unit of the Costa Rican Pacific coast (Fig. 1). It comprises an accretionary mélange formed during the Paleogene–early Neogene that is unconformably overlain by late Neogene to Quaternary subaeric and upper-slope sediments (Corrigan et al., 1990). Lew (1983) and Tournon (1984) documented biostratigraphic ages ranging from Late Cretaceous to Eocene for the accretionary complex. Berrangé and Thorpe (1988) and Berrangé et al. (1989) proposed a backarc origin for igneous rocks of the Osa Peninsula. These authors misinterpreted the outcrops of dark-colored, strongly deformed and diagenetically altered mudstones along the outer Osa coast as basaltic basement. Thick Neogene–Quaternary polymict conglomerates, including a suite of fresh ophiolitic rocks, with pyroxenites, gabbros, dolerites, and even foliated amphibolites (see Tournon, 1984), have been mapped in the upper reaches of most rivers on the peninsula. The Osa Peninsula can be excluded as a source area for these conglomerates, since none of these rock types crop out in the interior. The presence of sedimentary mélange in this area was first documented on Caño Island (Baumgartner, 1986) and then described from the outer Osa Peninsula (Obando, 1986; Baumgartner et al., 1989).

Mélangelike rock bodies are often associated with convergent plate margins. Raymond's (1984) definition of the term mélange fits well with field observations from central and outer Osa. The genesis of a mélange involves tectonic (e.g., offscraping, dismembered strata, etc.) and sedimentary (e.g., olistostromes) processes.

The Osa-Caño Accretionary Complex is subdivided into three units, characterized by matrix and associated blocks. These are: (1) the San Pedrillo unit, (2) the Cabo Matapalo unit, and (3) the Salsipuedes unit (Fig. 6). Detailed description and interpretation of the Osa-Caño Accretionary Complex are given in Di Marco (1994).

San Pedrillo Unit. The San Pedrillo Unit is well exposed along the northwestern tip of the Osa Peninsula, from Bahía Drake to Punta Llorona (Fig. 6). The Río Rincón, Río Cedral, and Río Tigre also have good exposures of this unit. The matrix includes blocks of dark graywacke (often siliceous), red radiolarian chert and mudstone (Bahía Drake, Río Cedral), and shallow-water redeposited limestones (Bahía Drake). The radiolarian chert and mudstone occur in sequences a few meters thick (Bahía Drake, Río Cedral) to hundreds of meters thick (Río Rincón) as dismembered interbeds in a matrix of volcaniclastic graywacke. Shallow-water carbonates are often included in the graywacke matrix as centimetric to metric clasts or blocks or as calciturbidites, supposed to originate from the inner wall of the trench.

Blocks of oceanic basalt and associated sediments (basaltic breccias, red radiolarian cherts/mudstones, red siliceous limestones) are found in variable amounts in the San Pedrillo Unit. These blocks are interpreted to have formed part of the subducting oceanic plate and to have been sporadically incorporated into the trench-fill sediments by offscraping and dismembering of the top of the incoming oceanic crust. Between Bahía Drake and San Pedrillo (Fig. 6), the ophiolitic component is locally very important and represents up to 80 to 90% of the volume of rocks. However, the basaltic bodies are always within a volcaniclastic sedimentary matrix. The age of the matrix is middle Eocene (Azéma et al., 1983). Lew (1983) proposed a late Paleocene to middle Eocene (most probably early Eocene) age for red radiolarian cherts included in basalt blocks near San Pedrillo.

Cabo Matapalo Unit. Typical sections for the Cabo Matapalo Unit crop out from Punta Carbonera to Cabo Matapalo on the southeastern tip of the Osa Peninsula (Fig. 6). Examples of this unit are also found in the Río Nuevo, Quebrada Piedras Blancas (a tributary to the Río Tigre), and the Río Sirena. The matrix of the mélange is generally a dark-brownish volcanic graywacke including, in minor amounts, bedded volcanic siltstones, sandstones, and breccias. Radiolarian cherts and redeposited shallow-water carbonates are absent. The age of the matrix has not been directly determined; however, an Eocene to Miocene age is probable according to the ages of the included blocks. The blocks are mainly light-brownish siliceous pelagic limestones that occur as one-meter to several-meters-sized bodies within the graywacke matrix. The limestones include planktonic foraminifers, calcified radiolarians, and sponge spicules. The siliceous fraction sometimes resulted in chert beds alternating with the micritic limestones. The chert beds are usually 10 cm thick and can represent more tan 60 to 70% of the rock volume. The limestones at Punta Carbonera include decimetric blocks of basalts. This observation suggests that these limestones represent the base of a sedimentary section overlying an oceanic basaltic basement. Blocks of basalts up to hundreds of meters across are found in the Río Sirena and in the Quebrada Piedras Blancas. The assemblages of planktonic foraminifers determined in the limestone blocks indicate ages ranging from late middle Eocene to middle Miocene. The outcrops between Punta Carbonera and Cabo Matapalo and the biostratigraphic control suggest that the limestone blocks originally formed a continuous pelagic sequence overlying a basaltic basement. Large bodies of this sequence were supposedly accreted by offscraping of the sedi-

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mentary cover of the incoming plate and subsequent tectonic dismembering and mélange formation.

Salsipuedes Unit. Prominent massive limestone bodies characterize the coastal promontory of Punta Salsipuedes (Fig. 6). These limestone bodies are up to 200 m across and occur in a dark-brown fine-grained graywacke matrix that also includes numerous smaller limestone blocks. In the coastal outcrops around Punta Salsipuedes, bedding is preserved in a large limestone block, and we can observe a steeply landward-dipping sequence of alternating meter-thick beds of pelagic limestone and 1- to 5-m-thick beds of shale and graywacke. Unfortunately, no well-preserved fossils could be extracted from this sequence. Phantoms of planktonic foraminifers suggest, however, a Paleocene-Eocene age. Lew (1983) and Tournon (1984) mention basaltic rock in this area. Our mapping cannot confirm this observation; however, dark-colored mudstone dikes crosscutting the white limestones are quite numerous. Azéma et al. (1981) reported a Paleocene age from outcrops near Quebrada Hedionda that are included with this unit. The Salsipuedes Unit probably represents an offscraped oceanic sequence that had little contact with trench-fill sediments. The nature of the limestone bodies and the origin of the interbedded fine graywackes require further investigation.

Burica Terrane

The Burica Terrane is represented by Late Cretaceous–Paleogene basement and associated sediments of the Burica Peninsula. The Burica Peninsula is a northwest-southeast–oriented promontory shaped by the Panama Fracture Zone (Fig. 1, Fig. 7). Structurally, the Burica Peninsula is a tilted fault block of oceanic basement and overlying Paleogene sediments on which thick Neogene (Pliocene-Quaternary) forearc sequences onlap with angular unconformity.

The Neogene sequences and the recent structure have been studied by Corrigan et al. (1990). Only one (unpublished) report exists on the Paleogene sequences (Obando, 1986). The outcrops of oceanic basalts and dolerites along the western coast of the Burica Peninsula (Fig. 7) contain some interflow sediments that have recently yielded Campanian radiolarians. At Playa Mangle, *Ranikothalia*-bearing shallow-water carbonate material occurs as infill in fissures penetrating several meters into an altered surface of oceanic basalt (Fig. 7). A discontinuous limestone bed, rich in resedimented shallow-water clasts mixed with planktonic foraminifers, covers the basalt surface (Fig. 7). Upsection, we measured a 30-m-thick sequence of siliceous pelagic limestone interbedded with mudstones and with limestone turbidites in the upper part. *Morozovella velascoensis* and other planktonic foraminifers that characterize the late Paleocene were identified both in the basal resedimented limestones and in the bedded pelagic limestones. Several Paleogene sections in rivers inland from Playa Mangle show similar sections, with a general increase in reworked shallow-water material toward the east. In the Quebrada Piedra Azul (Fig. 7), we measured a section of over 60 m comprising coarsening-upward limestone turbidites and breccias, overlain by a boulder bed, at least 20 m thick, containing middle Eocene larger foraminifers and rhodoliths. This limestone sequence is underlain by the same siliceous pelagic facies that form the top of the Playa Mangle sequence. However, the basaltic base of the section does not crop out in Quebrada Piedra Azul.

In the headwaters of Río Palo Blanco, Panama (Fig. 7), we observed large blocks of *Ranikothalia*-rich shallow-water limestones that occur near the base of the unconformable Neogene sediments. Even in the absence of good outcrop, these blocks suggest the presence of a late Paleocene carbonate platform in the immediate vicinity. In the Río Palo Blanco, we also discovered a more-than-50-m-thick sequence of siliceous limestones with interbedded turbidite and mass-flow deposits containing late Eocene shallow-marine material. The upper Paleocene–upper Eocene section described above is unique to the Burica Peninsula. The nearest other area that yielded late Paleocene–early Eocene pelagic lithologies with reworked *Ranikothalia*-bearing carbonates is the Quepos area.

The described outcrops suggest emergence of a basaltic area and the formation of an insolated carbonate platform since the late Paleocene, which lasted (probably with interruptions) until the late Eocene. Very proximal slope breccias (Quebrada Piedra Azul) and more distal carbonate turbidites suggest resedimentation of the platform carbonates into deep-water environments on the nearby slopes of an oceanic "seamount" (Obando, 1986). However, Frisch et al. (1992) reported an Island Arc Tholeiite (IAT) affinity of basaltic rocks exposed along the Costa Rican coast of Burica. Overturned pillow basalts found along the coast near Playa Mangle indicate that the basaltic basement underwent important tectonization prior to the deposition of the upper Paleocene–upper Eocene sequence. We therefore interpret the emergence of the Burica basement as the result of a tectonic event that affected a portion of a Late Cretaceous primitive island arc near the western edge of the thickened Caribbean-type crust. Post-Eocene plate convergence and strike-slip transport along the western edge of the Caribbean plate brought the Burica Terrane into its present position.

PALEOMAGNETIC DATA

We focused our paleomagnetic sampling on Upper Cretaceous and Paleocene sedimentary rocks outcropping in southwestern Costa Rica and western Panama. The sampled area includes the Chorotega, Nicoya, Golfito, and Burica Terranes. We drilled 34 sites along the Pacific coast and three sites near the Caribbean northwestern coast of Panama (Fig. 8; Table 1), with an average of 10 samples per site. We preferably sampled fine micritic limestones with biostratigraphic age control. From a total of 37 sites, five are from Paleogene limestone blocks included in the Osa-Caño Accretionary Complex and are not presented in this study. Thirteen sites sampled in

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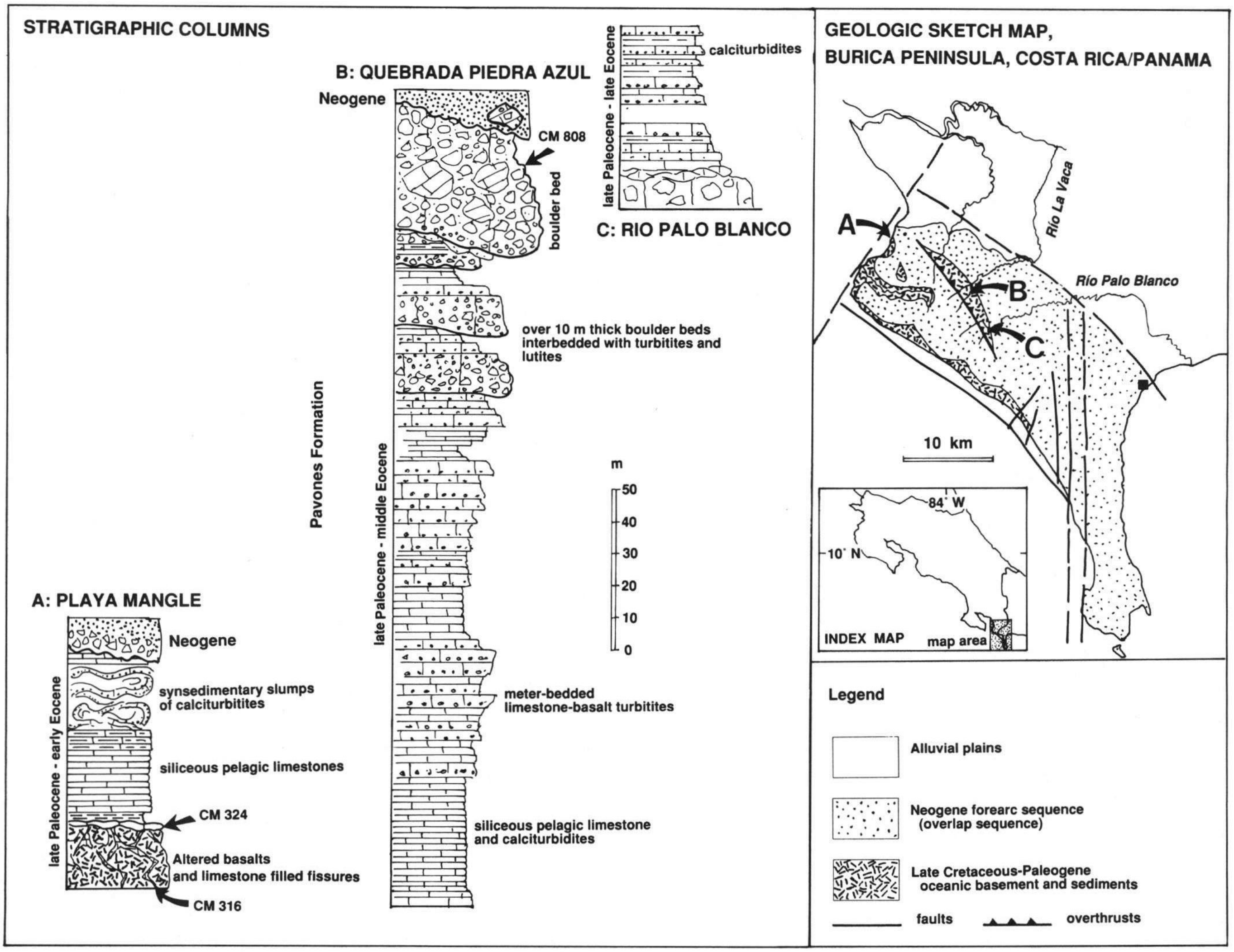

Figure 7. Sketch map of the Burica Peninsula and representative stratigraphic columns of the pre-Neogene stratigraphy. Sections include data from Obando (1986).

Upper Cretaceous pelagic limestones were discarded as a result of either unstable demagnetization behavior or poor within-site grouping of magnetization components ($\alpha_{95} > 16$). A total of 19 sites yielded magnetization components with sufficiently good within-site grouping.

For all samples collected in this study, progressive thermal demagnetization in 50°, 25°, or 15°C steps was carried out until the magnetization intensity dropped close to magnetometer noise level. The magnetization vector during progressive demagnetization was plotted in orthogonal projection. The magnetization component directions were derived by visually picking straight-line segments from the orthogonal projections and using the standard principal component analysis (Kirschvink, 1980) to compute the component direction. For some sites both a high unblocking temperature (HBT) and a low unblocking temperature (LBT) component could be resolved. The site mean magnetization components were computed by combining sample magnetization components using Fisher (1953) statistics (Table 1).

Chorotega Terrane

Changuinola River (Panama). A section of Upper Cretaceous limestones crops out in the upper part of the Changuinola River, near the western Caribbean coast of Panama (Changuinola Formation; Fisher and Pessagno, 1965). Sites 20 and 21 were drilled in light-gray to white micritic bioturbated limestones, close to the confluence of the Río Culubre with the Changuinola River (Peña Blanca locality; Fig. 8). At site 20, the limestones include poorly preserved planktonic foraminifers. The presence of *Globotruncanita stuarti* and *Globotruncana ventricosa* confirms the late Campanian–early Maastrichtian age given by Fisher and Pessagno (1965).

These limestones showed variable behavior during ther-

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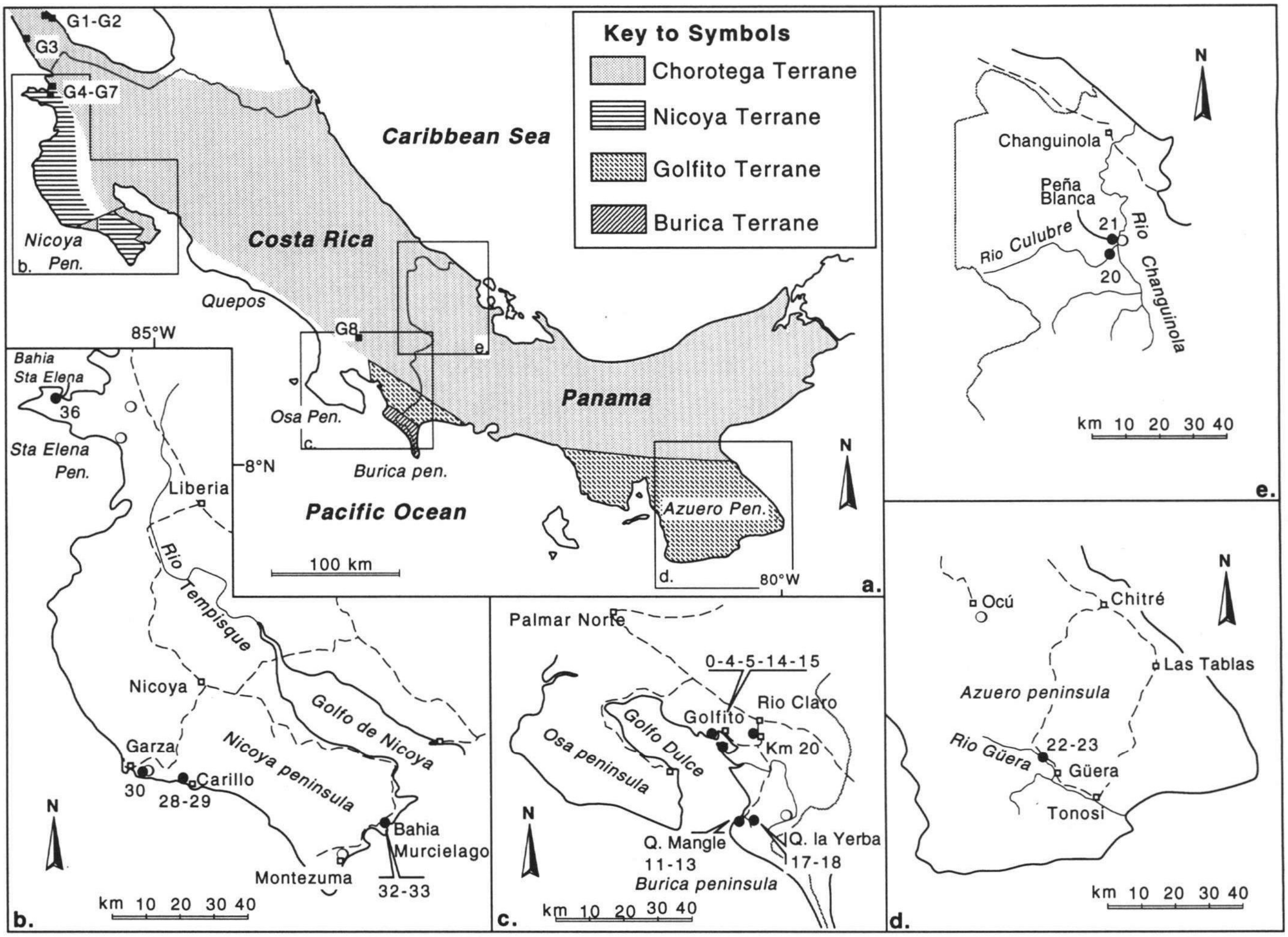

Figure 8. a, Distribution of the Late Cretaceous–Paleogene tectonostratigraphic terranes of Costa Rica and western Panama with location of Gose's (1983) paleomagnetic sites (solid squares). b through e, Location of paleomagnetic sites of this study (solid circles); open circles represent rejected sites.

mal demagnetization (Fig. 9). Samples from site 20 exhibited a discrete blocking temperature spectrum in the 500 to 600°C temperature range. Blocking temperatures are more distributed for site 21, and a magnetization component was usually defined in the 400 to 500°C temperature range. The HBT components of site 20 cluster around a south and shallow up direction after structural tilt correction (Fig. 10). Magnetization component directions resolved from site 21 cluster in the antiparallel direction, except for one sample that provides a component almost parallel to the HBT components from site 20 (Fig. 10). The presence of dual polarity magnetization components and the improved antiparallelism of the component directions after tilt correction (Fig. 10) suggest the presence of a primary magnetization component at these two sites. The precision (K) of the mean of the two site means improves markedly after structural tilt correction (Table 2).

Nicoya Peninsula. At Puerto Carrillo (sites 28, 29; Fig. 8), basaltic breccias are overlain by several tens of meters of upper Campanian to Maastrichtian calciturbidites with thin interbeds of fine gray-black calcareous mudstones (Baumgartner et al., 1984). The section at Bahía Murcielago in southeastern Nicoya Peninsula (Fig. 8) includes well-exposed light-gray to light-green limestones, changing to red marly limestones in the upper part of section. We sampled sites 32 and 33 just below this contact: site 32 at Punta Murcielago and site 33, 150 m to the south. The two sites are separated by a minor fault, but site 33 clearly lies above site 32 in view of their position relative to the contact with the marly limestones. At both sites, we identified a middle Maastrichtian foraminiferal assemblage (Table 3; Plate I on p. 25), which can be correlated to the gansseri Zone of Robaszynski et al. (1984).

At Puerto Carrillo and Bahía Murcielago (sites 28, 29, 32, 33), an LBT component was defined below the 350°C demagnetization step, and a major component (HBT) was resolved in most of the samples in the 350 to 625°C temperature range. For some samples from site 28, the HBT component was re-

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TABLE 1. PALEOMAGNETIC DATA FROM COSTA RICA AND PANAMA

Site ID	Age	Component		Before Tilt Correction					After Tilt Correction				
and Location		Designator	N	R	Decl.	Incl.	K	a95	R	Decl.	Incl.	K	a95
					Golfito Region								
(0) Pta Curupacha	U. Camp.	HBT	6N	5.7	300.5	15.9	18.1	16.2	5.8	297.5	2.4	29.1	12.6
(4) Km 20	Mid. Maast.	HBT	9N	8.5	315.1	-11.4	17.4	12.7	8.6	315.3	13.8	17.9	12.5
		LBT	8	7.5	8.5	23.4	14.0	15.4	7.6	20.6	29.5	16.1	14.2
(5) Playa Cacao	Camp./Maast.	HBT	8N	7.8	306.2	18.6	40.0	8.9	7.8	306.9	6.1	34.5	9.6
		LBT	7	4.8	6.2	30.7	2.8	44.6	4.8	2.3	19.7	2.7	45.5
(14) Pta Curupacha	U. Camp.	HBT	13N	12.8	311.6	25.1	53.9	5.7	12.8	307.5	6.4	55.8	5.6
		LBT	6	5.9	0.2	27.1	83.5	7.4	5.9	348.2	20.3	62.7	8.5
(15) Pta El Cabro	Camp./Maast.	HBT	15N	14.7	292.1	38.0	52.8	5.3	14.7	293.1	-3.0	52.7	5.3
		LBT	10	9.7	9.2	39.7	29.0	9.1	9.7	347.8	19.2	28.8	9.2
					Burica								
(11) Up Q. Mangle	U. Paleoc.	HBT	5R	4.9	94.4	11.3	75.6	8.9	4.9	98.4	-19.4	71.2	9.1
		LBT	9	8.8	13.5	21.4	39.7	8.3	8.8	11.1	-32.2	33.4	9.0
(13) Down Q. Mangle	U. Paleoc.	HBT	8R	7.9	124.3	-30.1	63.7	7.0	7.9	119.0	-13.7	63.7	7.0
		LBT	8	7.7	9.4	19.6	27.3	10.8	7.7	1.0	24.0	27.2	10.8
(17) Q. La Yerba	U. Paleoc./Eoc.	HBT	12R	11.9	82.2	-0.3	74.8	5.1	11.9	84.7	-8.6	75.1	5.0
(18) Q. La Yerba	U. Paleoc./Eoc.	HBT	9R	8.6	94.4	-4.5	22.4	11.1	8.6	99.3	-13.0	22.4	11.1
		LBT	8	7.6	2.0	34.7	28.1	10.6	7.8	5.6	4.2	28.2	10.6
					Panama								
(20) Rio Changuinola	Camp./Maast.	HBT	12R	11.9	162.7	3.8	179.1	3.3	11.9	161.9	-7.7	190.4	3.2
(21) Rio Changuinola	Camp./Maast.		10N/1R	10.6	341.3	11.5	28.1	8.8	10.6	339.8	14.1	28.2	8.7
(22) Rio Güera	U. Cret.	HBT	11R	10.8	97.4	13.1	58.3	6.0	10.8	100.1	0.9	58.1	6.0
(23) Rio Güera	U. Cret.	HBT	7R	6.9	99.3	33.5	40.6	9.6	6.9	103.3	3.2	58.1	8.0
					Nicoya–Sta Elena								
(28) Playa Carrillo	Camp./Maast.	HBT	11N	10.6	351.9	27.8	26.9	9.0	10.7	347.3	11.3	29.3	8.6
(29) Playa Carrillo	Camp./Maast.	HBT	9R	8.9	169.1	-43.6	64.3	6.5	8.9	156.6	-19.4	64.0	6.5
(32) Bahia Murcielago	Mid. Maast.	HBT	11R	10.7	164.6	-43.8	30.3	8.4	10.7	177.8	-22.2	30.2	8.4
(33) Bahia Murcielago	Mid. Maast.	HBT	9N	8.7	8.1	49.8	28.0	9.9	8.8	5.1	12.4	35.7	8.7
(30) Playa Garza	Mid. Maast.	HBT	14N/R	12.8	338.0	-10.4	10.6	12.8	12.8	324.4	-17.0	10.9	12.6
		LBT	16	14.4	15.0	3.4	8.7	13.2	14.3	15.0	3.4	8.7	13.2
(36) Bahia Sta Elena	Camp./Maast.	HBT	10N/R	9.7	342.3	13.5	26.0	9.6	9.8	340.2	-21.3	27.8	9.3
					Previous Workers								
(G1) Nicaragua	U. Cret.		18		356.4	24.3	71.9	4.1		352.8	32.4	72.3	4.1
(G2) Nicaragua	U. Cret.		11		3.9	15.8	264.6	2.8		1.6	21.7	262.4	2.8
(G3) Nicaragua	Paleoc.		20		178.9	-4.2	56.3	4.4		176.3	-16.0	56.6	4.0
(G4) Sta Elena	U. Cret.		14		2.4	29.0	87.6	4.3		1.7	-08.6	63.6	5.0
(G7) Sta Elena	Eoc.(?)		27		0.3	22.8	65.3	3.5		1.0	-14.1	44.3	4.2

solved after demagnetization at temperatures above 500°C. The HBT magnetization components for sites 28, 29, 32, and 33 cluster into two groups of directions, which are either north-northwest and down or south-southeast and up after tilt correction (Fig. 11). According to the middle Maastrichtian age and stratigraphic superposition of sites 32 and 33, we conclude that the negative inclinations of site 32 were acquired during chron C31R and the positive inclinations of site 33 during chron C31N (Fig. 12).

Nicoya Terrane

Site 30 is located at Playa Garza, on the southwestern coast of the Nicoya Peninsula (Fig. 8). Near the eastern end of Playa Garza, intercalations of light-red marly limestone are observed within a thick sequence of gently folded basaltic conglomerate overlying a basaltic basement (Baumgartner et al., 1984). We sampled two lenses of the red marly limestones assigned to the middle Maastrichtian, gansseri Zone of Robaszynski et al. (1984) (Plate I on p. 25, Table 3; see also Schmit-Effing, 1979).

On the Santa Elena peninsula, along the northern coast, Upper Cretaceous to Eocene sediments crop out. We sampled site 36 in the Bahía Santa Elena, toward the western end of the beach (Fig. 8). The section is floored by shallow-water limestones bearing rudist fragments and orbitoids and overlain by basaltic breccia. Some ten m of red to gray pelagic limestones

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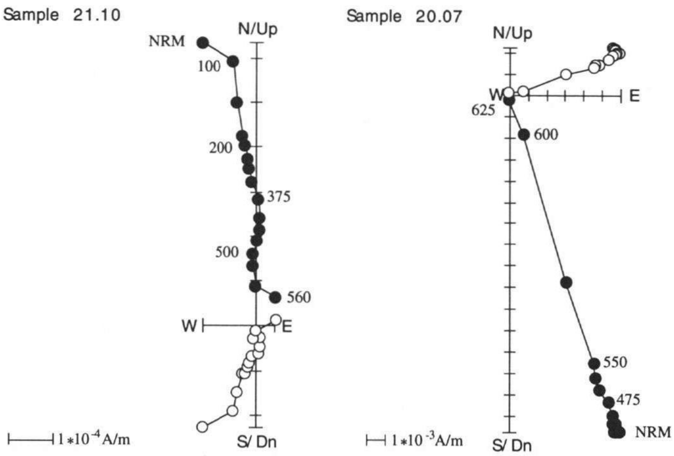

Figure 9. Orthogonal projections of thermal demagnetization data from Changuinola Formation (sites 20 and 21), after tilt correction. Open and solid circles represent projection on the vertical and horizontal planes, respectively. The temperatures in degrees Celsius are indicated for some of the demagnetization steps.

overlying the breccias were sampled for paleomagnetism, avoiding turbidites present in the upper part. A sample collected within the first 0.5 m of pelagic limestones provided a planktonic foraminifer assemblage that places the base of the pelagic sequence into the uppermost Campanian (calcarata Zone, Robaszynski et al., 1984) (Table 3, Plate I on p. 25). The sampled section is overlain by a coarsening-upward turbiditic sequence.

The red marly limestones from Garza and Santa Elena (sites 30, 36) yielded two magnetization components (Fig. 13). Below 250/350°C, an LBT direction was resolved. Above 300°C, the HBT component can be defined. Above 650°C, the directions became scattered. The LBT components of site 30 at Playa Garza cluster around the present field direction before tilt correction (Fig. 14). They are interpreted to be of Recent origin. The HBT components are poorly grouped and orientated northwest and up or southeast and down (Fig. 14). The HBT components with northwest declinations and negative inclinations are observed in the top 0.5 m of the sampled section and overlie the samples with southeast declinations. In view of the middle Maastrichtian age (gansseri Zone) of the section, the northwest declinations and negative inclinations are correlated to chron C31N (Fig. 12). This implies that the site originated in the Southern Hemisphere.

At Bahía Santa Elena, the HBT directions from site 36 lie along two antiparallel directions, which are either northwest and up or southeast and down. The negative inclinations appeared at the base of the sampled section (between 0 and 0.55 m) and at the top (above 1.65 m). Four samples collected between 0.80 and 1.20 m yielded positive inclinations (Fig. 15). The assemblage of planktonic foraminifers observed in samples collected at the base of the section (0.20 m) indicated a late Campanian age (calcarata Zone) (see above). Since this biozone correlates to a time of normal polarity (chron 33N) (Fig. 15), the basal negative inclinations must have been recorded in a normal polarity field. This implies a south equatorial paleolatitude for site 36, as for the Playa Garza site (site 30).

Golfito Terrane

Golfito region. Sites 0 and 14 were sampled at Punta Curupacha, a coastal outcrop on the northeastern side of the Golfo Dulce (Fig. 8). At this locality, fine white micritic limestones stratigraphically overlie pillow basalts. Planktonic foraminifers

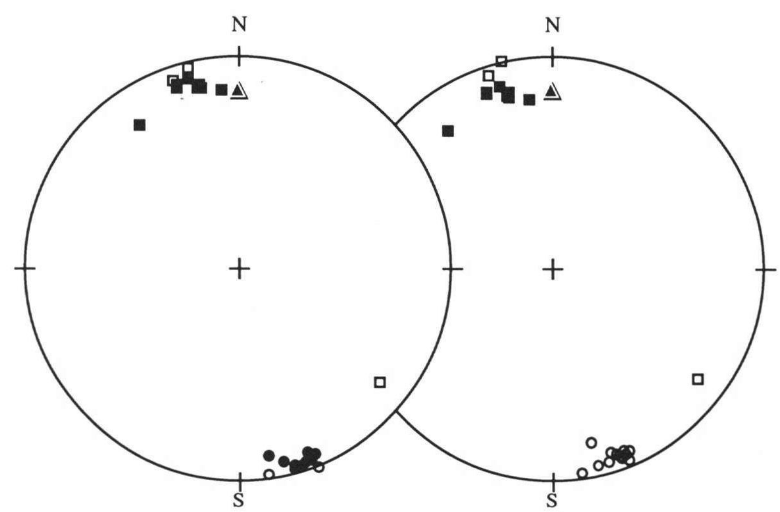

Figure 10. Equal area projection of high unblocking temperature magnetization components before (left) and after (right) tilt correction for sites 20 (circles) and 21 (squares) at Changuinola. Solid and open symbols represent positive (downward) and negative (upward) inclinations, respectively. The triangle represents the Present field direction.

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TABLE 2. GROUPING OF SITE MEAN DIRECTIONS

Group ID	Group of Sites	N	Before Tilt Correction R	Decl.	Incl.	K	a95	After Tilt Correction R	Decl.	Incl.	K	a95
Chorotega Block	20,21,28,29,32,33,G1, G2,G3	9	8.5	352.7	24.4	15.6	13.4	8.8	350.9	17.7	44.4	7.8
	28,29,32,33,G1,G2,G3	7	6.7	356.3	30.1	20.5	13.6	6.9	354.0	19.6	49.4	8.7
	28,29,32,33	4	3.9	172.9	-41.6	46.7	13.6	3.9	351.8	16.6	38.8	14.9
	20,21	2	2.0	342.0	3.9	55.7	34.1	2.0	340.9	10.9	290.5	14.7
Nicoya Terrane	30,36,G4,G7	4	3.8	350.3	14.1	15.1	24.4	3.8	347.1	-15.8	20.1	21.0
	30,36	2	1.9	340.1	1.6	22.4	55.6	2.0	332.2	-19.3	56.4	34.5
Golfito Terrane	0,4,5,14,15,22,23	7	6.2	297.9	6.0	7.9	23.0	6.8	297.6	3.1	31.8	10.9
	0,4,5,14,15	5	4.8	306.4	18.1	17.4	18.9	4.9	304.8	5.4	46.1	11.4
	22,23	2	2.0	98.3	23.3	31.4	46.2	2.0	101.7	2.1	846.4	8.6
Burica Terrane	11,13,17,18	4	3.7	98.1	-6.0	11.4	28.5	3.9	100.3	-14.0	31.6	16.6

TABLE 3. BIOSTRATIGRAPHY AT SAMPLING SITES

Tertiary: Paleocene P5	P4	P3	P2	P1	Upper Cretaceous: Middle Maastricht. G. gansseri Zone	Lower Maastricht. Gtr. falso-stuarti Zone	Upper Campanian Gta. calca-rata Zone	Sites	*A. mckannai*	*A. primitiva*	*M. conicotruncata*	*M. aequa*	*M. velascoensis*	*G. gansseri*	*Glla. citae*	*Glla. havanensis/citae*	*Glla. havanensis*	*Rugoglobigerina* sp.	*Rugotruncana* sp.	*R. contusa*	*Gta. angulata*	*R. fornicata*	*Rosita* sp.	*Gta. stuarti*	*Gta. stuartiformis*	*Gta. stuarti/stuartiformis*	*Gtr. falsostuarti*	*Gtr. linneiana*	*Gtr. bulloides*	*Gtr. ventricosa*	*Gta. subspinosa*	*Gta. calcarata*
					▬			32, 33	|	|	|	|	|	*	*	|	|	|	|	*	*	|	|	*	*	|	*	*	*	*	|	|
					▬			30	|	|	|	|	|	*	|	|	|	*	|	*	*	*	|	*	*	|	*	*	|	*	|	|
							▬	36 (base)	|	|	|	|	|	|	|	|	|	|	|	|	|	*	|	|	|	|	|	*	|	*	|	*
							▬	0, 14	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|	*	|	|	|	|	*	*	*
						▬		5	|	|	|	|	|	|	|	*	|	|	|	|	|	|	*	|	*	*	|	*	*	*	|	|
					▬			4	|	|	|	|	|	|	|	|	*	|	*	|	*	*	*	*	|	|	|	*	*	*	|	|
▬	▬							11, 13	*	*	*	*	*	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|

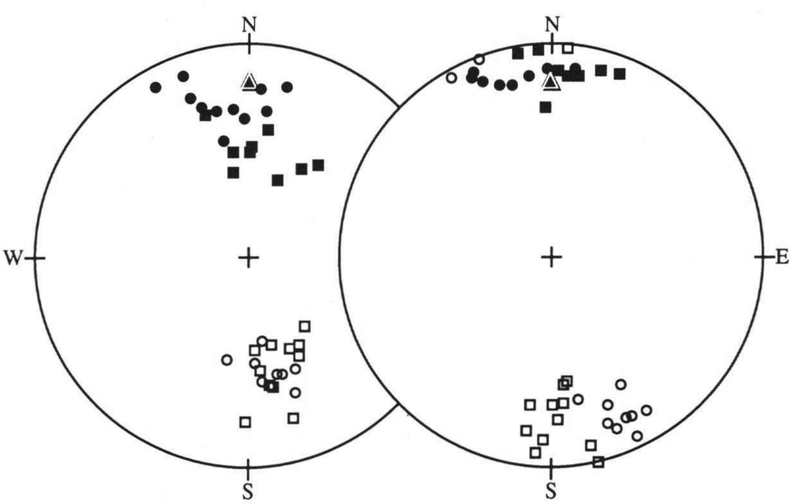

Figure 11. Equal area projection of high unblocking temperature components before (left) and after (right) tilt correction for sites 28 and 29 at Puerto Carrillo (circles) and 32 and 33 at Bahía Murcielago (squares). Symbols as for Figure 10.

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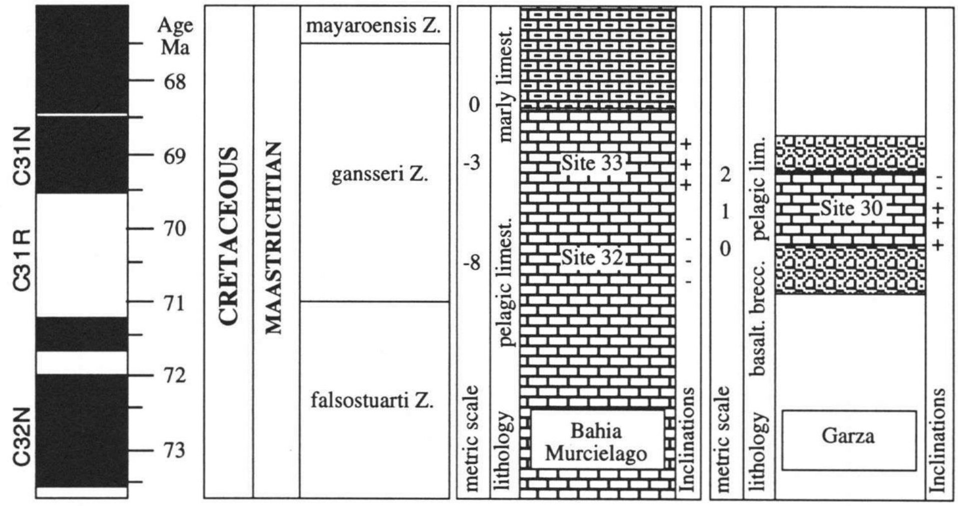

Figure 12. Correlation of the lithostratigraphy at Bahía Murcielago (sites 32, 33) and Garza (site 30) to the geomagnetic polarity timescale (GPTS) using the foraminiferal biozonation. Biozones refer to Robaszynski et al. (1984) and correlation to the GPTS follows Kent and Gradstein (1985).

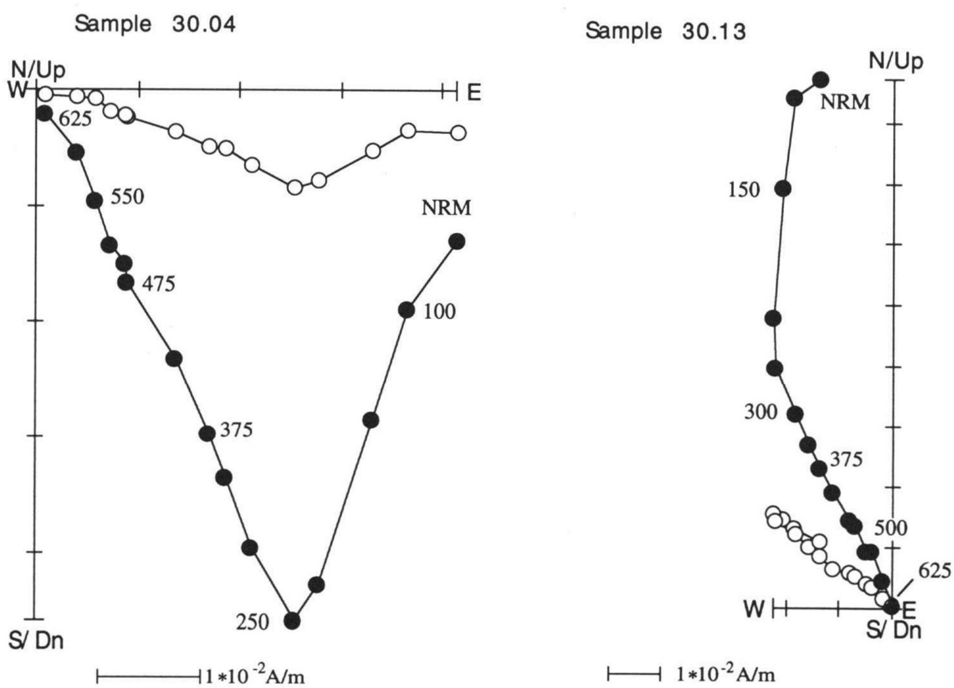

Figure 13. Orthogonal projections of thermal demagnetization data from Garza limestones (site 30), after tilt correction. Symbols as for Figure 9.

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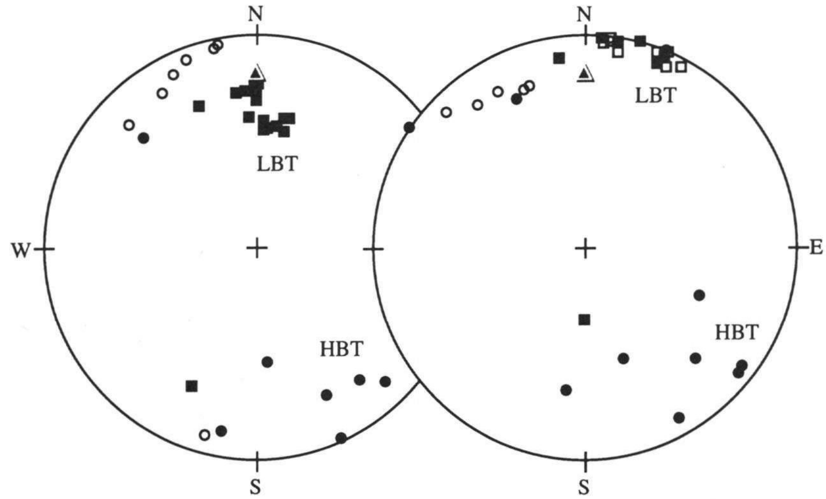

Figure 14. Equal area projection of HBT (circles) and LBT (squares) components before (left) and after (right) tilt correction for Garza (site 30). Symbols as for Figure 10.

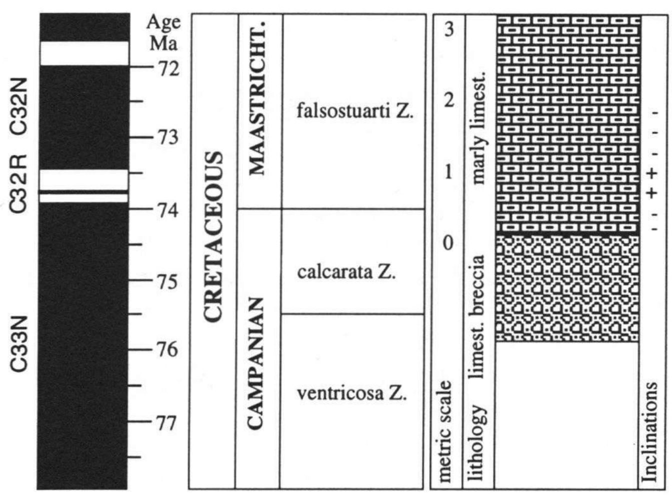

Figure 15. Correlation of the lithostratigraphy at Bahía Santa Elena (site 36) to the GPTS using the foraminiferal biozonation. References as for Figure 12.

are abundant in the limestones. We determined a faunal assemblage indicating a latest Campanian age (calcarata Zone; Robaszynski et al., 1984; Table 3). Site 5 was sampled at Playa Cacao (Fig. 8) in white to gray laminated micritic limestones interbedded with calcilutites. The planktonic foraminifers observed (Table 2) tend to place the section in the falsostuarti Zone of the early Maastrichtian (Robaszynski et al., 1984). Site 15 was sampled at Punta el Cabro, south of Golfito (Fig. 8), in white micritic limestones in fault contact with massive dolerites. Site 4 is located at the locality "km 20" on the Golfito–Río Claro road (Fig 8). To the west side of the road, white micritic limestones crop out. They include centimetric levels rich in organic matter that form a regular black lamination. The faunal assemblage fixes the age to the middle Maastrichtian (gansseri Zone; Robaszynski et al., 1984; Table 3).

The Golfito sites (sites 0, 4, 5, 14, 15) exhibited multicomponent magnetization during thermal cleaning (Fig. 16). Below 350°C, LBT magnetization directions were defined in nearly all the samples. Above 350°C, an HBT component was removed. Between 570 to 580°C, the major part of the intensity has been removed and the directions become scattered. The LBT components from the Golfito sites give directions almost parallel to the present Earth's field before tilt correction (e.g., site 14, Fig. 17) and are therefore interpreted to be of recent origin. The HBT components cluster around a northwest and shallow direction after tilt correction (e.g., site 14, Fig. 17). The overall mean of HBT components from all five Golfito site means passes a regional fold test at the 95% confidence level (McElhinny, 1964) (Table 2). The HBT components therefore predate the (probably) Paleogene folding (see above).

Azuero Peninsula (Panama). Few outcrops of Upper Cretaceous sediments are known from the Azuero Peninsula. We sampled thin calcareous interbeds intercalated in volcanic arenites from the so-called Güera Formation exposed on the banks of Río Güera (sites 22 and 23), approximately 10 km north of Güera village (Fig. 8). The sampled lithologies include calcified radiolaria and debris of planktonic foraminifers, but the age could not be precisely determined.

For the Güera Formation (sites 22, 23), an LBT component was defined below demagnetization temperatures of 200°C and an HBT in the 200 to 580°C range (Fig. 18). The HBT component does not always decay to the origin of the projection, suggesting the presence of an additional magnetization component, but as magnetization directions became scattered above 580°C, this final component could not be resolved. The HBT components from the Güera sites (22, 23) cluster after tilt correction around an east and shallow direc-

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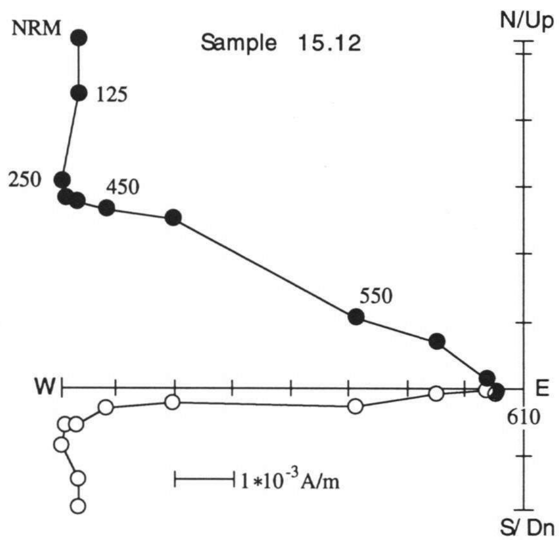

Figure 16. Orthogonal projection of thermal demagnetization data from Golfito limestones (site 15), after tilt correction. Symbols as for Figure 9.

tion. The two site mean directions are very similar after structural tilt correction (Table 1), and the precision of the mean of the two site means improves after tilt correlation (Table 2), giving a positive fold test at the 95% confidence level using the criteria of McElhinny (1964).

Burica Terrane

The sampled sections on the Burica Peninsula include pelagic siliceous limestones interbedded with redeposited shallow-water sediments overlying oceanic basalts and dolerites. At Playa Mangle and in the Mangle and La Yerba rivers, upper Paleocene to middle Eocene limestones crop out. Sites 11 and 13 were sampled in micritic limestones and calcilutites from the Mangle river (Fig. 8). The planktonic foraminiferal assemblage indicates that the sediments are late Paleocene in age (Zone P4-P5 from Toumarkine and Luterbacher, 1985; Table 3). Sites 17 and 18 are located in the La Yerba river (Fig. 8), where fine calcilutites rich in calcified radiolaria were sampled. These sediments are thought to be of late Paleocene–middle Eocene age (Obando, 1986).

The Burica samples (sites 11, 13, 17, 18) showed multicomponent magnetization, and two component directions could generally be defined (Fig. 19). During the first steps of demagnetization (100 to 200°C) an LBT component could be defined, and an HBT component was resolved in the 200 to 500°C temperature range. The observable LBT components from sites 11, 13, and 18 all more or less correspond before tilt correction to the present field direction (e.g., site 11, Fig. 20) and are thought to be of Recent origin. The HBT directions cluster around an east and shallow up direction after tilt correction. The precision (K) of the overall mean from the four Burica sites improves after structural tilt correction (Table 2); however, the improvement is insufficient to constitute a positive regional fold test.

DISCUSSION OF THE PALEOMAGNETIC RESULTS

The site mean magnetization directions were grouped according to the newly proposed tectonostratigraphic subdivision of the Costa Rican landbridge (Fig. 21). The overall mean for each group of site mean directions was calculated using Fisher (1953) statistics (Table 2). The data from Gose (1983) are included in the analysis. The data of Frisch et al. (1992) are not included in the analysis as these data are difficult to evaluate. In Frisch et al. (1992) indeed, the site mean declinations and locality mean declinations are variable, with shallow scattered inclinations. As the data are based on blanket demagnetizations

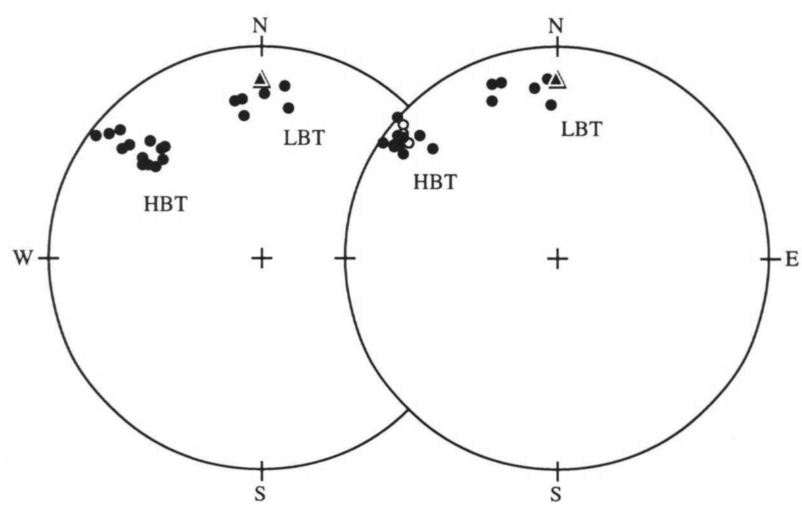

Figure 17. Equal area projection of HBT and LBT components before (left) and after (right) tilt correction for one Golfito site (site 14). Symbols as for Figure 10.

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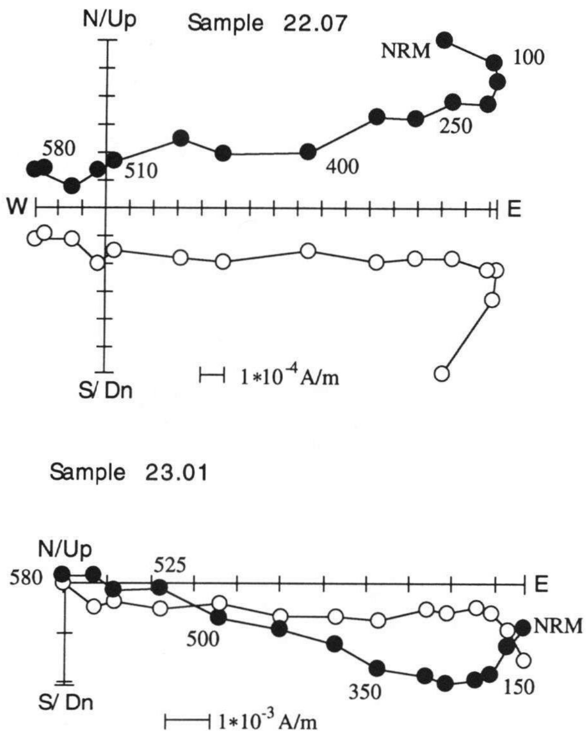

Figure 18. Orthogonal projections of thermal demagnetization data from Güera sediments (sites 22 and 23), after tilt correction. Symbols as for Figure 9.

(at peak alternating fields of 15mT or at temperatures in the 350 to 400°C range), part of the within-site and between-site scatter may be due to single magnetization components' not having been resolved. Furthermore, the structural correction for the sites derived from basalts (more than 60% of the sites included in the study) was made using the anisotropy of magnetic susceptibility (AMS), assuming that the short axes of the AMS coincides with the pole of bedding of the nearby sedimentary rocks. Figure 7 of Frisch et al. (1992) demonstrated, on the contrary, that these two directions are different (over 10°); therefore, their structural corrections are inexact for the igneous lithologies. Blanket demagnetizations and inexact structural corrections may be the reason for the scatter of the data.

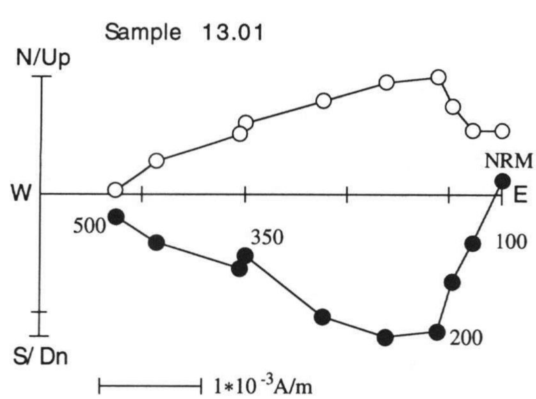

Figure 19. Orthogonal projection of thermal demagnetization data from Burica limestones (site 13), after tilt correction. Symbols as for Figure 9.

Chorotega Terrane

The first group of paleomagnetic data includes sites 28, 29, 32, 33 located in the Nicoya Peninsula (Puerto Carrillo, Bahía Murcielago); sites G1, G2, G3 (Gose, 1983) from southern Nicaragua; and sites 20, 21 sampled in northwestern Panama (Changuinola river). Site G8 of Gose (1983) was not included in the data set since it was sampled from sediments that probably are Oligocene in age. The Chorotega Terrane fold test is positive at the 95% level of confidence ($N = 9$; $k2/k1 = 2.85$; Table 2) using the McElhinny (1964) criteria. This implies that the site mean directions comprise magnetization components that predate the folding. This result mainly depends on the Changuinola data, which are well grouped after tilt correction (sites 20, 21; Table 2). Without sites 20 and 21, the site mean directions do not pass the fold test at the 95% confidence level, although the grouping is improved ($N = 7$; $k2/k1 = 2.41$). Furthermore, reversals were observed at each of the localities. Although reversals are no guarantee that a rock unit is not remagnetized, they add reliability to the result (Van der Voo, 1990).

The Chorotega Terrane group of data is characterized by mean paleomagnetic directions (Decl = 350.9; Incl = 17.7; $\alpha_{95} = 7.8°$) approximately parallel, after tilt correction, to present-day Earth's field (Table 2; Fig. 21). The paleopole of this mean direction lies at 81.1°N, 180.4°E. This pole is not distinct at the 95% confidence level from the Late Cretaceous (70 Ma) mean paleopole for South America (Irving and Irving, 1982). Therefore, we conclude that the Chorotega Terrane underwent no significant rotation relative to South America and no significant northward shift. This result implies that the sum of latitudinal displacement of the Caribbean plate, relative to South America, between the Late Cretaceous and the Present is not significant (Fig. 22). Site G8 (Gose, 1983) suggests a southward displacement of the Chorotega Terrane between Late Cretaceous (70 Ma) and Oligocene (30 Ma). More data are needed to confirm this trend.

Nicoya Terrane

Sampling sites associated with the Nicoya Terrane include the Santa Elena sites and some sites on the Nicoya Peninsula (sites 30, 36, G4, G7). The mean paleomagnetic direction after tilt correction for this group of sites is northward with negative inclination (Decl = 347.1° and Incl = –15.8°, $\alpha_{95} = 21.0°$) (Table 2, Fig. 21). Reversals observed at sites 30 and 36 improve the reliability of the result, although we have no field test to constrain the age of these site mean magnetizations. The detailed biostratigraphy of the sampled sites leads us to conclude that the northerly overall mean di-

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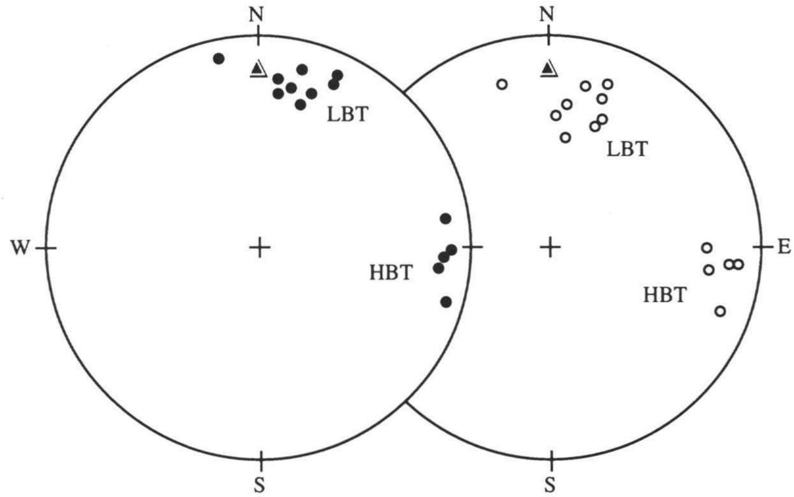

Figure 20. Equal area projection of HBT and LBT components, before (left) and after (right) tilt correction for one Burica site (site 11). Symbols as for Figure 10.

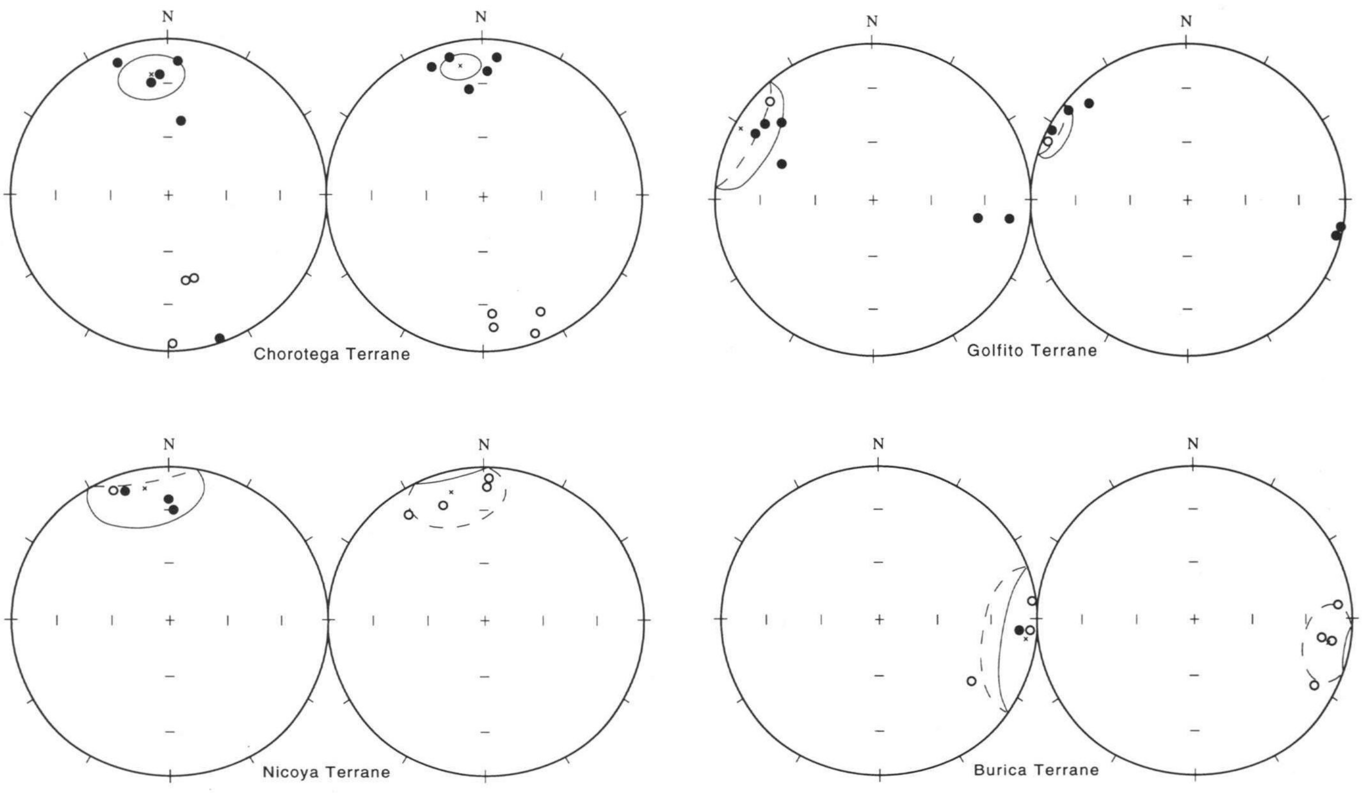

Figure 21. Equal area projections of site mean directions before (left) and after (right) tilt correction for each tectonostratigraphic unit defined in this chapter. Symbols as for Figure 10.

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rection represents a normal polarity direction, indicating a small counterclockwise rotation and a low south-equatorial paleolatitude in the Late Cretaceous (Table 2, Fig. 22). In spite of the large error associated with this mean, the data are significantly different at the 95% confidence level from the Chorotega Terrane data (e.g., the 95% confidence ellipses do not overlap; Table 2, Fig. 21). The poor precision of the overall mean is due to scattered site mean declinations, which are probably a result of local tectonic rotations.

Golfito Terrane

The sites associated with the Golfito Terrane (sites 0, 4, 5, 14, 15, 22, and 23) are from the Golfito and Azuero areas. The overall mean direction after tilt correction (Decl = 297.6°, Incl = 3.1°, α_{95} = 10.9°) (Table 2, Fig. 21) is characterized by very shallow inclinations. The precision of the overall mean improves substantially after structural tilt correction, constituting a positive fold test at the 95% significance level (N = 7; k2/k1 = 4.03; Table 2) using the McElhinny (1964) criteria. The Golfito sites alone (sites 0,, 4, 5, 14, 15), in the absence of the Güera sites (22, 23), do not pass the fold test, but the precision value does increase on structural tilt correction (N = 5; k2/k1 = 2.65).

The polarity determinations based on foraminiferal biostratigraphy correlated with the magnetic polarity timescale imply about 60° counterclockwise rotation of the Golfito Terrane relative to the Chorotega Terrane, combined with a small northward shift, since Late Cretaceous time.

Burica Terrane

The paleomagnetic data from the Burica Peninsula are associated with the Burica Terrane. The paleomagnetic mean direction of the Burica group of sites (Decl = 100.3° and Incl = –14.0°, α_{95} = 16.6°) is not distinct at the 95% confidence level from either the Golfito or the Güera groups of sites (Fig. 21, Table 2). However, as documented above, the stratigraphy of the Burica Peninsula is completely different from that from Golfito Terrane. We consider that the terrane underwent since the late Paleocene a very small northward migration from low northerly latitudes, with a counterclockwise rotation of about 90° relative to the Chorotega Terrane. The polarity uncertainty implies an alternative solution with a south equatorial origin of the Burica Terrane. This would imply a northward shift of about 15° between the late Paleocene and the Eocene.

CONCLUSIONS

The Chorotega Terrane constitutes most of the southern Middle American Landbridge and was the western edge of the Caribbean Plate during the Late Cretaceous–Paleocene. Paleomagnetic data for the Chorotega Terrane indicate an origin close to its present latitude and no significant rotation relative to South America since the Late Cretaceous.

The Nicoya Terrane includes the Nicoya Complex (*sensu stricto*), a thrust complex including three units of oceanic origin, unconformably overlain by Upper Cretaceous and Tertiary sedimentary rocks. Lower Cretaceous to middle Paleocene detrital facies are dominated by basaltic material derived from

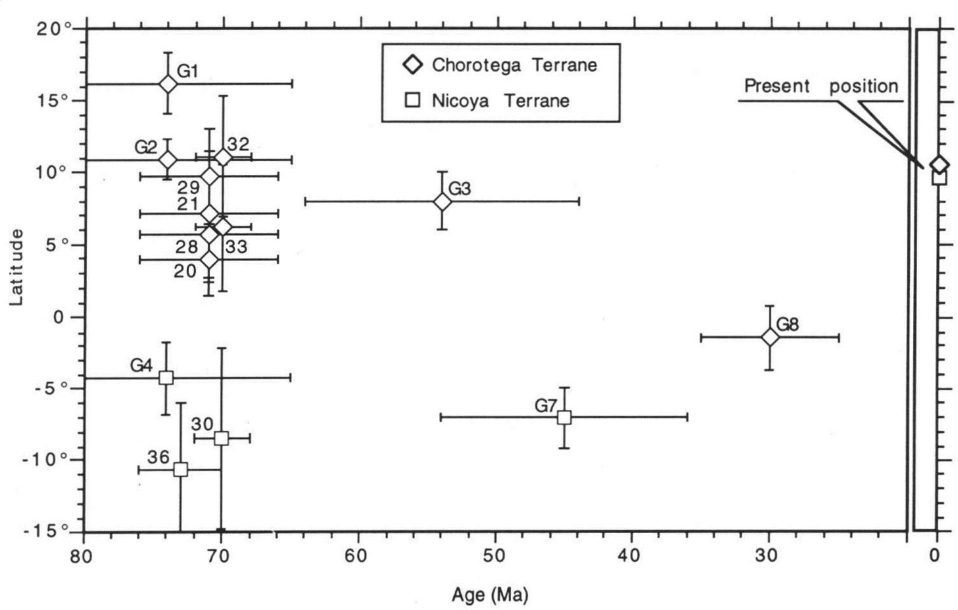

Figure 22. Paleolatitude of the Chorotega Terrane and Nicoya Terrane data sets. Numbers refer to the site numbers; G1 to G8 refer to sites from Gose (1983) (Table 1). Vertical error bars are the paleolatitude uncertainties calculated on the base of the Fisher (1953) α_{95} values for each site. Horizontal lines show ranges in age.

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local erosion within the terrane. Late Paleocene channel-fill deposits contain large andesitic boulders marking the initial amalgamation of the Nicoya Terrane with the Chorotega Terrane. The paleomagnetic data obtained from the Nicoya Terrane indicate a low southerly Late Cretaceous paleolatitude with almost no rotation relative to the Chorotega Terrane. The Nicoya Terrane was positioned about 16° of latitude south of the position of the Chorotega Terrane, in Late Cretaceous times. The pre-Campanian Nicoya Complex (*sensu stricto*), therefore, must have originated in the Pacific, at quite some distance from its present position. Consequently, the term Nicoya Complex (*sensu stricto*) should no longer be applied to oceanic basement areas of Central America, distinct from the Nicoya Terrane.

The Golfito Terrane is composed of a sequence of volcano-sedimentary rocks including: (1) a basaltic basement, (2) a sequence of interbedded volcanic flows and sediments of Campanian–middle Maastrichtian age, and (3) a volcaniclastic sequence. The paleomagnetic data from the Golfito Terrane indicate a Late Cretaceous equatorial paleolatitude and a counterclockwise rotation of about 60° relative to the Chorotega Terrane. The basement of the Golfito area is thought to have formed a marginal piece of the Caribbean oceanic plateau, transported northward by strike slip along the rim of the Caribbean plate.

The volcanic basement of the Burica Terrane (Burica Peninsula) is overlain by proximal shallow carbonate debris flows that suggest a near carbonate platform mounted on an emergent piece of a primitive island arc. The paleomagnetic data from the Burica Terrane indicate a low northerly paleolatitude in the Paleocene, slightly south of its present position, and a counterclockwise rotation of nearly 90° relative to the Chorotega Terrane. A south equatorial origin of the Burica Terrane and, thus, a northward shift of about 15° between the late Paleocene and the middle Eocene are not excluded, although these are less likely considering the reduced northward shift of the Farallon and Caribbean plates during this time.

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Plate I. Selected species of Late Cretaceous planktonic foraminifers from sampled sections at Bahía Murcielago (1 through 7), Playa Garza (8 through 11), and Bahía Santa Elena (12 through 15). Species: (1) *Globotruncanella citae;* (2, 3) *Gansserina gansseri;* (4, 8) *Globotruncanita angulata;* (5, 9) *Rosita fornicata;* (6, 10) *Rosita contusa;* (7) *Globotruncana linneiana;* (11) *Globotruncanita stuarti;* (12, 13, 14) *Globotruncanita calcarata;* (15) *Globotruncana ventricosa.* Scale A for all figures except figures 10 and 11, which are Scale B.

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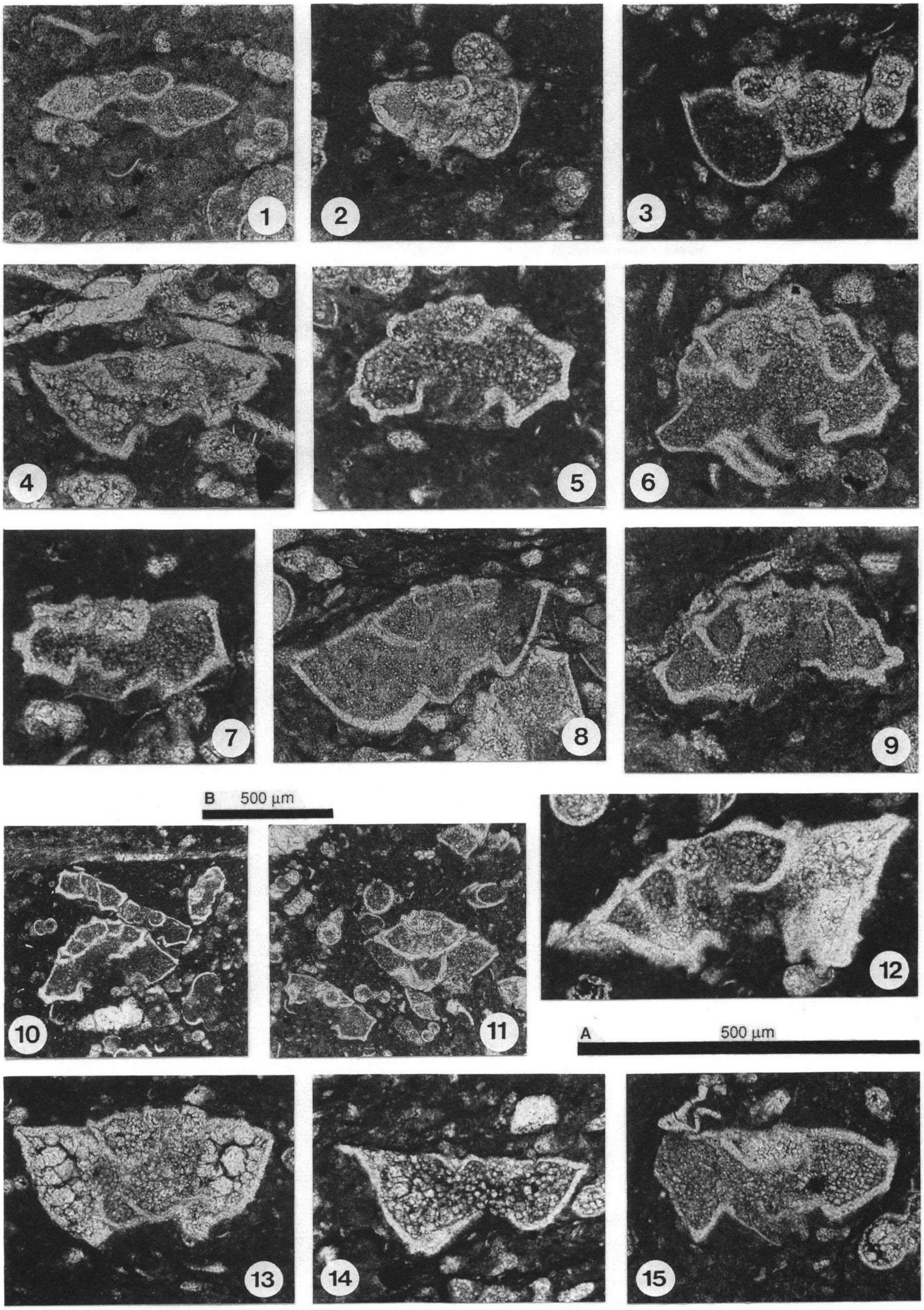

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