

The Geology of the Darien, Panama, and the late Miocene-Pliocene collision of the Panama arc with northwestern South America

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ABSTRACT

The geology of the Darien province of eastern Panama is presented through a new geologic map and detailed biostratigraphic and paleobathymetric analysis of its Upper Cretaceous to upper Miocene sediments. The sequence of events inferred from the stratigraphic record includes the collision of the Panama arc (the southwestern margin of the Caribbean plate) and South American continent. Three tectonostratigraphic units underlie the Darien region: (1) Precollisional Upper Cretaceous–Eocene crystalline basement rocks of the San Blas Complex form a series of structurally complex topographic massifs along the northeastern and southwestern margins of the Darien province. These rocks formed part of a >20 m.y. submarine volcanic arc developed in a Pacific setting distant from the continental margin of northwestern South America. The northerly basement rocks are quartz diorites, granodiorites, and basaltic andesites, through dacites to rhyolites, indicating the presence of a magmatic arc. The southerly basement rocks are an accreted suite of diabase, pillow basalt, and radiolarian chert deposited at abyssal depths. Precollisional arc-related rocks, of Eocene to lower Miocene age, consist of 4000 m of pillow basalts and volcanics, and biogenic calcareous and siliceous deep-water sediments. They consist of the Eocene-

Oligocene Darien Formation, the Oligocene Porcona Formation and the lower-middle Miocene Clarita Formation. Postcollisional deposits are mostly coarse- to fine-grained siliciclastic sedimentary rocks and turbiditic sandstone of upper middle to latest Miocene age. This 3000 m thick sedimentary sequence is deformed as part of a complexly folded and faulted synclinorium that forms the central Chucunaque-Tuira Basin of the Darien. The sedimentary package reveals general shallowing of the basin from bathyal to inner neritic depths during the 12.8–7.1 Ma collision of the Panama arc with South America. The sediments are divided into the upper middle Miocene Tapaliza Formation, the lower upper Miocene Tuira and Membrillo Formations, the middle upper Miocene Yaviza Formation, and the middle to upper Miocene Chucunaque Formation.

The precollisional open marine units of Late Cretaceous–middle Miocene age are separated from the overlying postcollisional sequence of middle to late Miocene age by a regional unconformity at 14.8–12.8 Ma. This unconformity marks the disappearance of radiolarians, the changeover of predominantly silica deposition from the Atlantic to the Pacific, the initiation of the uplift of the isthmus of Panama, and the onset of shallowing upward, coarser clastic deposition. This pattern is also recorded from the southern Limon Basin of Caribbean Costa Rica to the Atrato Basin of northwestern Colombia. By the middle late Miocene, neritic depths were widespread throughout the Darien region, and a regional unconformity suggests completion of the Central American

arc collision with South America by 7.1 Ma. No Pliocene deposits are recorded from either the Darien or the Panama Canal Basin, and no sediments younger than 4.8 Ma have been identified in the Atrato Basin of Colombia, suggesting rapid uplift and extensive emergence of the Central American isthmus in the latest Miocene.

Northward movement of the eastern segment of the Panama arc along a now quiescent Panama Canal Zone fault during Eocene–Oligocene time may have dislocated the precollision arc. Since collision, the portion west of this fault (Chorotega Block) has remained stable, without rotation; to the east, in the Darien region, compression has been accommodated through formation of a Panama microplate with convergent boundaries to the north (North Panama deformed belt) and south (South Panama deformed belt), and suturing with South America along the Atrato Valley. Deformation within the microplate has been accommodated in the Darien province by several major left-lateral strike-slip faults that were active until the early Pliocene, since when the plate has behaved rigidly.

Keywords: Neogene, stratigraphy, paleobathymetry, Darien, Panama, Central American Isthmus.

INTRODUCTION

The synthesis of the Neogene history of the Darien province of eastern Panama provides an opportunity to evaluate the timing and effects of the collision of the southern Central American

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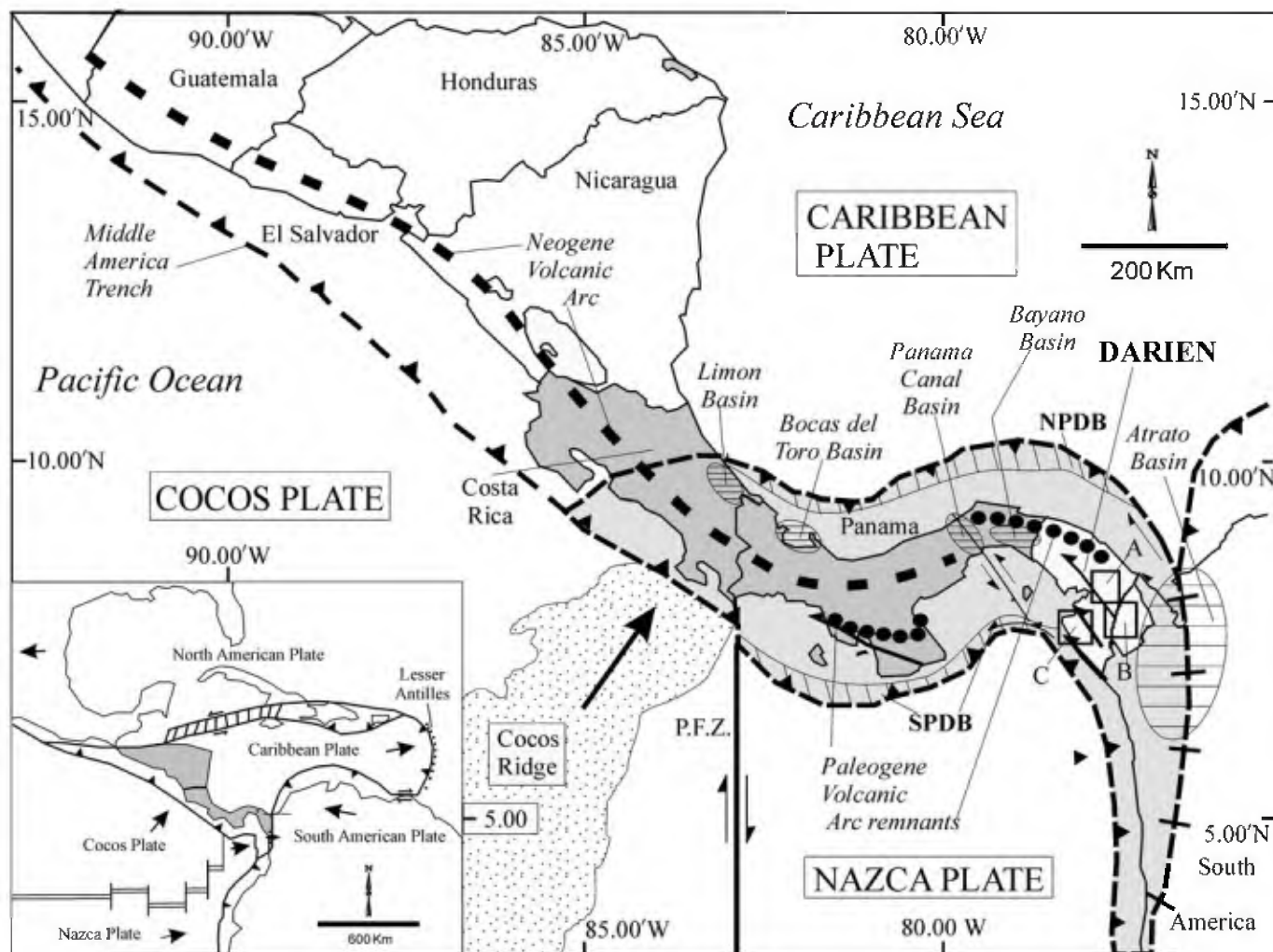


Figure 1. Map of southern Central America (dark shading) and the Panama microplate (pale shading). Darien is picked out in pale shading. Dashed lines with teeth mark zones of convergence; zippered line is Panama-Colombia suture. Very heavy dashed line marks location of Neogene volcanic arc; black circles mark Paleogene-Eocene volcanic arc. NPDB—North Panama deformed belt; SPDB—South Panama deformed belt; PFZ—Panama fracture zone. Principal Neogene sedimentary basins located by striped ovals. Boxes A, B, and C indicate the location of the maps in Figures DR48–DR50 (see footnote 2).

volcanic arc with the South American plate. The deposits of the Chucunaque-Tuira and Sambu Basins (Fig. 1) are correlative with sequences in the Atrato Basin, northwestern Colombia (Duque-Caro, 1990a, 1990b), the Panama Canal Basin, central Panama (Collins et al., 1996a), the Bocas del Toro Basin, western Panama (Coates, 1999; Coates et al., 1992, 2003), and the Limon Basin, Costa Rica (Cassell and Sen Gupta, 1989; Astorga et al., 1991; Seyfried and Hellmann, 1994; Collins et al., 1995). We reconstruct the various stages in the collision of Central and South America through the interpretation of a new geologic map of the whole region (Fig. 2), detailed biostratigraphic and paleobathymetric

analyses of the syn- and postcollisional Neogene sediments that fill the Chucunaque-Tuira and Sambu Basins, and a review of the Upper Cretaceous through Oligocene formations described in published and unpublished reports of earlier fieldwork. Data for this paper were collected on six expeditions made to the Darien (1990–1996) by the Panama Paleontology Project (PPP; Collins and Coates, 1999).

PREVIOUS WORK

The earliest geological surveys of the Darien (Carson, 1874; Maack, 1872; Wyse, 1877) were conducted as part of explorations for a ship canal across the Isthmus of Panama. Gold mining in the Darien produced geological surveys

locally (Woakes, 1899; Low, 1931), but the first regional surveys were undertaken for oil exploration (Fig. 3). Shelton (1952) carried out detailed geological fieldwork in the Chucunaque River and Tuira River valleys of the Darien province, but the first regional account was that of Terry (1956), who had conducted fieldwork throughout Panama between 1929 and 1949.

The geology of three possible routes for a new transisthmian canal, carried out by the Office of Interoceanic Canal Studies (OICS), was summarized by Bandy (1970) and Bandy and Casey (1973). Esso Exploration and Production Panama (1970, 1971) provided a series of measured sections and a preliminary geologic map for parts of eastern Panama and Darien provinces. We have used data from these reports (with

¹Figure 2 is on an insert accompanying this issue.

		Beckelmyer (1947), Sinclair Oil Co. Report	Shelton (1952)	Terry (1956)	McReady & Ward, (1960) Delhi-Taylor Oil Co. Report	Bandy and Casey (1973)		Esso Report (1970)	This study								
		Central Darien Province		Eastern Panama	Darien Province	Atlantic Side	Pacific Side	Darien Basin	Chucunaque-Tuira Basin		Tuira Basin	Sambu Basin					
						Paralic and non-marine beds											
Pliocene	Upper	Chucunaque Fm.	Chucunaque Fm.	Chucunaque Fm.										Syn- post-collisional rocks			
	Middle																
	Lower																
Miocene	Upper	Pucro Fm.	Pucro Fm.	Gatun Fm.	Pucro Mbr.	Pucro Fm.	Sabana Beds		Lara Group	Chucunaque Fm.	Chucunaque Fm.		Tuira Fm.				
	Middle	Lower Gatun Fm.	Lower Gatun Fm.		Lower Gatun Fm.	Gatun Fm.				Pucro Fm.	Yaviza Fm.	Membrillo			Tuira Fm.	Tapaliza Fm.	
Lower	Aquaqua Fm.	Aquaqua Fm.	Aquaqua Fm.	Aquaqua Fm.	Pacific Tuffs		Clarita Lst. ?	Capeti Fm.	Clarita Mbr.	Clarita Fm.		Clarita Fm.	Pre-collisional rocks				
Upper	Arusa Shale	?	Arusa Fm.	Arusa Fm.					Porcona Mbr.	Porcona Fm.		?					
Middle	?	Arusa Shale		?													
Lower	Clarita Fm.	Clarita Fm.		Clarita Fm.	Clarita Fm.				Coliscordia Mbr.	?							
Eocene	Upper	Corcona Fm.		Eocene	Corcona Fm.	Morti Tuffs		Darien Fm.	Tuquesa Mbr.	Darien Fm.							
	Middle	?	Agglomerate						?	?							
	Lower																
Paleocene		?		Chert ?	?			San Blas Fm.	Caobanera Fm.	San Blas Complex							
Cretaceous		Basement		Complex					Punta Sabana Fm.								

Figure 3. Summary of previous Darien region lithostratigraphic nomenclature from published and unpublished reports.

permission from the Panamanian Ministry of Hydrocarbons), and from Terry (1956), Bandy and Casey (1973), Stewart (1966), MacDonald (1969), Wing and MacDonald (1973), and Mann and Kolarsky (1995), and combined them with our results to construct the geological map (Fig. 2). Oil company data were used mainly to delineate the Cretaceous through Oligocene outcrops; we mapped all Neogene formations. We formalize below the lithostratigraphy of the Neogene succession of the Darien, retaining previously unpublished names where appropriate, and we provide a detailed biostratigraphic correlation and paleobathymetric interpretation for each formation. We then use this framework, together with previous research on southern Central America to northern Colombia, to trace

the uplift of the Isthmus of Panama and collision of Central and South America.

METHODS

Field Sampling/Mapping

The Pan-American Highway is the only road that penetrates eastern Panama, reaching as far eastward as Yaviza, some ~50 km from the Colombian border (Fig. 2). Access to most of the region is by motorized dugout canoe. Fresh Neogene exposures in the Chucunaque-Tuira Basin of the Darien are confined to eroded riverbanks, as reflected in our sampling localities (Figs. DR48–DR50).² Detailed logs are provided in the data repository (DR) for each section.

Location, age, and stratigraphic information for PPP sampling sites can be accessed from the PPP database at <http://www.fiu.edu/~collins/>.

Biostratigraphy

Biostratigraphic control (Table 1) was provided by planktic foraminifera (Berggren) and calcareous nannoplankton (Aubry). Foraminiferal samples were washed over a 63 µm sieve, and residues were air-dried. Varsol was used to

²GSA Data Repository item 2004169, logs referred to herein as Figs. DR40–47, and maps of PPP sample sites as Figs. DR48–50, is available on the Web at <http://www.geosociety.org/pubs/ft2004.htm>. Requests may also be sent to editing@geosociety.org.

disaggregate indurated samples with high clay content. Planktic foraminifera were picked from the 63 μm and 149 μm residues. Smear slides were prepared for all nannofossil samples and examined with a Zeiss photomicroscope at $\times 200$, $\times 600$, and $\times 1250$ magnifications. We used the biozonal schemes of Martini (1971) for calcareous nannoplankton and Blow (1979) and Berggren et al. (1995) for planktic foraminifera. The biochronologic age estimates are from Berggren et al. (1995). In this paper, we maintain a nomenclatural distinction between the lowest (LO) and highest (HO) stratigraphic occurrence and the first/evolutionary (FAD) and last/extinction (LAD) temporal occurrence.

Biozonal assignments for calcareous nannoplankton were based on the presence/absence of marker species as determined from a scan of a minimum 7.2 cm^2 area. This permitted the recovery of specimens showing the characteristic features upon which to confidently establish the occurrence of particular marker taxa. This was critical for establishing the range of discoasters that are essentially distinguished by the characters of the fragile arm tips, such as *Discoaster hamatus*, *D. neohamatus*, and *D. calcaris*. This also permitted the recovery of markers that are extremely rare in these assemblages, such as *Catinaster coalitus* (only one verified specimen) and *Discoaster kugleri* (only two specimens encountered). Diagenesis and silicification from weathering explain the scarcity of such taxa and the generally impoverished assemblages in most samples.

As no ceratoliths occur in these rocks, the absence of *Discoaster neohamatus* was tentatively used to characterize the upper part of zone NN11 (subzones NN11b–d; the HO of *D. neohamatus* immediately preceding the LO of *Amaurolithus primus*; Aubry, 1993). Also, the occurrence of this species was substituted for that of *Catinaster calyculus* to characterize subzone NN9b. As in the Buff Bay section of Jamaica, the LO of *Globorotalia plesiotumida* in the Darien sections occurs in zone NN10, not in zone NN11 as commonly recorded (see Berggren, 1993). Thus, we have based age estimates for upper Miocene intervals primarily on calcareous nannofossils rather than planktic foraminiferal datums (Table 1).

Paleoenvironmental Analysis

Benthic foraminiferal assemblages contained in 45 Miocene samples in eight river sections (Figs. DR40–DR47) from the Chucunaque-Tuira and Sambu Basins of Darien were analyzed to determine the sequences of paleobathymetries. Specimens were prepared using the methods of Collins (1993) and typically

identified to the species level (Table 2). Preservation varies from excellent to extremely poor.

Living species of benthic foraminifera are bathymetrically zoned (Natland, 1933; Bandy, 1953) and have water depth distributions that are comparable in different areas (Murray, 1991). Neogene assemblages consist of both extant and extinct species. In our bathymetric reconstruction we have relied primarily on current depth ranges of extant species in the tropical to subtropical eastern Pacific (e.g., Smith, 1964; Golik and Phleger, 1977). For extinct taxa, estimates were based on recurrent associations with extant species that have been documented for the eastern Pacific coast (e.g., Ingle, 1980; Finger, 1990).

Physiographic divisions (such as upper, middle, and lower) of the continental shelf and slope occur on average at similar water depths around the world. However, water depths associated with these physiographic divisions vary considerably along the coast from California to Central and South America (summarized by Smith, 1964), so the physiographic ranges of benthic foraminiferal species were converted to their equivalent water depths for studies of Recent benthic foraminifera (Bandy and Arnal, 1957; Smith, 1964; Golik and Phleger, 1977). Because downslope redeposition of sediments is common near the continental margin, the paleobathymetric determinations emphasize the upper depth limits of the deepest-dwelling species in the assemblages.

In addition to the paleobathymetry, low-oxygen depositional conditions were also identified in the sediments. Dissolved oxygen in bottom waters and sediments strongly influences tropical eastern Pacific benthic foraminiferal associations (Smith, 1964). Assemblages within the oxygen-minimum zone, which occurs today between 50 m and 1600 m off Central America, have certain taxa found in abundance under these conditions relative to normal oxygenation (e.g., *Bulimina uvigerinaformis*, *Bolivina hootsi*; Ingle, 1967). Under low-oxygen conditions, specimens commonly have small, thin-walled tests, and assemblages are of low diversity. Diversity was measured with Fisher's α (Fisher et al., 1943), an index that takes into account both the number of specimens and the number of species, which are correlated. The number of species in the Darien assemblages varied from 10 ($\alpha = 2$) to 73 ($\alpha = 25$). Assemblages with $\alpha < 6$ and taxa characteristic of oxygen deficiency were inferred to have lived under low-oxygen conditions.

GEOLOGICAL SETTING

The geological setting for the rocks of the Chucunaque-Tuira and Sambu Basins (Fig. 2) is that of a Late Cretaceous–Eocene island arc develop-

TABLE 1. LIST OF PLANKTIC FORAMINIFERA AND CALCAREOUS NANNOFOSSIL RANGES USED TO DATE THE FORMATIONS LISTED IN TABLE 2

	FAD	LAD
Calcareous Nannofossils		
<i>Amaurolithus primus</i>	NN11b	
<i>Discoaster quinqueramus</i>	8.6	
<i>Discoaster bollii</i>		NN10
<i>Discoaster brouweri</i>	NN10	
<i>Discoaster misconceptus</i>	NN10	
<i>Discoaster pentaradiatus</i>	NN10	
<i>Discoaster surculus</i>	NN10	
<i>Discoaster neohamatus</i>	NN9b	ca. 7.8
<i>Catinaster calyculus</i>	NN9b	
<i>Discoaster hamatus</i>	10.5	9.4
<i>Discoaster calcaris</i>	NN8	
<i>Catinaster coalitus</i>	10.9	
<i>Coccolithus miopelagicus</i>		10.8
<i>Discoaster exilis</i>		NN8
<i>Discoaster musicus</i>	NN5	NN7
<i>Discoaster kugleri</i>	11.8	
<i>Discoaster petaliformis</i>	NN4	NN5
<i>Sphenolithus heteromorphus</i>	18.2	13.6
<i>Helicosphaera ampliaperta</i>		15.6
Planktic Foraminifera		
<i>Globorotalia plesiotumida</i>	8.3	
<i>Globigerinoides obliquus extremus</i>	8.3	
<i>Neoglobobulimina acostaensis</i>	10.9	
<i>Paragloborotalia mayeri</i>	11.4	
<i>Globoturborotalita nepenthes</i>	11.8	
<i>Globorotalia fohsi</i>	12.7	
<i>Globorotalia praefohsi</i>	12.7	
<i>Globorotalia peripheroacuta</i>	14.8	
<i>Globorotalia peripheroronda</i>	14.6	
<i>Orbulina suturalis</i>	15.1	
<i>Praeorbulina glomerosa</i>	16.1	
<i>Praeorbulinba sicanus</i>	16.4	

Note: Datum levels of stratigraphically useful planktic foraminifera and calcareous nannofossils used in this study. Age estimates are from Berggren et al. (1995) except for the FAD of *D. hamatus*, which is an astrochronologic estimate (Hilgen et al., 2000). We have used the biochronologic of Berggren et al. (1995) rather than the more accurate astrochronologic age estimates of Hilgen et al. (2000) to preserve consistency between ages of calcareous nannoplankton and planktic foraminiferal datums.

ing as a result of the interaction of the Caribbean, South American, Cocos, and Nazca plates as first shown by Molnar and Sykes (1969). The southern Central American arc occupied the southern part of the western margin of the Caribbean plate from Upper Cretaceous time and moved generally eastwards through the Cenozoic to collide with South America in the Neogene. The eastern margin of the Panama arc in Colombia is defined by the Atrato-Uraba fault, the collisional suture with continental South America (Trenkamp et al., 2002). The location of this suture is shown in Figure 1. An extensive review of the regional tectonic history of the western margin of the Caribbean plate is provided by Mann (1995) and references therein.

Our study records primarily the history of tectonic collision of the Panama arc and South America and only indirectly sheds light on the timing of closure of the Pacific-Caribbean seaway. The timing of the initial collision had previously been estimated at between 10 and 20 Ma (Wadge and Burke, 1983; Trenkamp et al., 2002). After ca. 5 Ma, the collision and resulting uplift of the Panama arc had forced the reorganization of global oceanic circulation (Keigwin, 1982; Keller et al., 1989; Haug and Tiedemann, 1998), with major changes in Caribbean and eastern Pacific organic, carbonate, and silica production (Droxler et al., 1998; Roth et al., 2000) and in the distribution of marine macro- and microfaunas (Duque-Caro, 1990a; Jackson et al., 1993; Collins et al., 1996b). Closure of the Pacific-Caribbean seaway by 3 Ma allowed the terrestrial Great American Biotic Interchange (Marshall, 1985; Marshall et al., 1979; Webb, 1985) between North and South America.

Precollisional magmatic basement rocks and associated sediments underlie the San Blas and Darien Massifs (Fig. 2), an unbroken structural arch that extends into Colombia as the Dabeiba

arch (Duque-Caro, 1990b). The postcollisional Neogene sediments occupy the small Sambu Basin half graben (Fig. 2) and fill the large Chucunaque-Tuira Basin, a thick, folded, sedimentary sequence that forms a central lowland paralleling the San Blas and Darien Massifs. Northwestward, this sequence passes into the Bayano Basin (Stewart, 1966); southeastward it is continued into Colombia as the Atrato Basin (Duque-Caro, 1990a; Fig. 1). Precollisional accretionary basement rocks form the Mahé, Sapó, Bagre, Jungurudo, and Pirre Massifs (Fig. 2), each separated by major faults.

For the syn- and postcollisional sediments (plus the upper Clarita Formation) that are the focus of this paper, we provide logs (Figs. DR40-DR47) that show the stratigraphic relations of all the PPP sites and formally define the lithostratigraphic units. We provide a new detailed biochronology (Fig. 4; Table 3) and paleobathymetric estimates (Fig. 5) for each unit, together with a correlation to other southern Central American sequences described previously (Figs. 6 and 7). Lastly, we attempt an analysis of the sedimentary his-

tory and the tectonic features derived from the geologic map (Fig. 2) to constrain the timing of collision of the southern Central American arc with the South American plate.

PRECOLLISIONAL (CAMPANIAN-MIDDLE MIOCENE) BASEMENT ROCKS

The oldest reliably dated rocks in the Darien belong to a Campanian accretionary volcanic arc complex (Bandy, 1970; Bandy and Casey, 1973). Together with their magmatic arc equivalents, they form the basement complex of the Darien, herein described as the San Blas Complex (Figs. 2 and 3). The San Blas Complex is unconformably overlain by the Eocene-Oligocene Darien Formation (Fig. 3). Eocene units of the Darien Formation were first referred to as the Morti Tuffs, and Oligocene units (occurring only in the southwest) as the Pacific Tuffs (Bandy, 1970; Bandy and Casey, 1973). To the northeast in the San Blas Massif, the Oligocene is represented by the Porcona Formation. The Darien and Porcona Formations are regionally

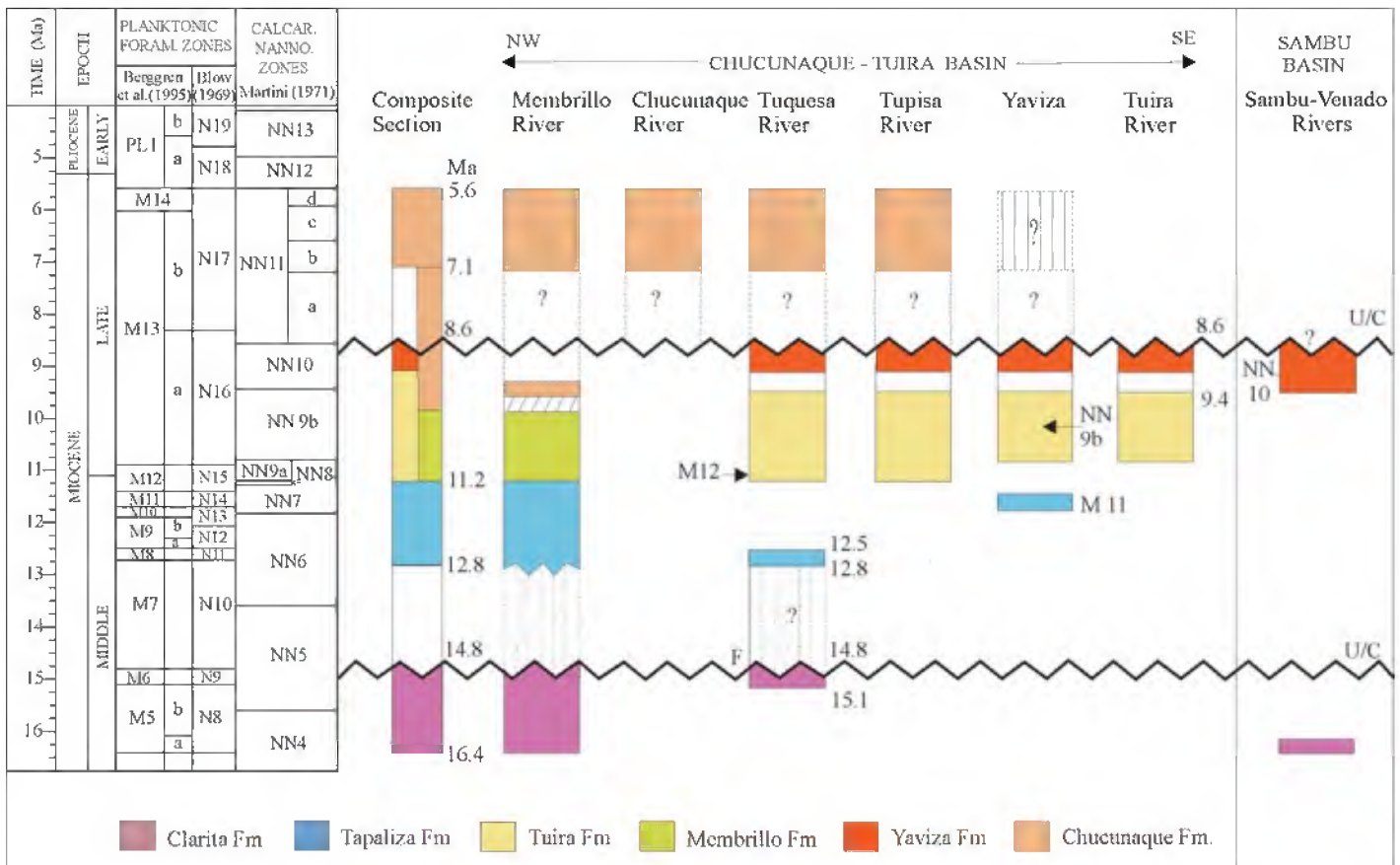


Figure 4. Correlation of the Neogene formations of the Darien region. Wavy thick lines indicate the two major regional unconformities at ca. 14.8 Ma and 8.6 Ma.

overlain by the Clarita Formation, of which we have studied the upper part.

San Blas Complex

On the northeastern flank of the Chucunaque-Tuira Basin, in the San Blas and Darien Massifs, the San Blas Complex is a magmatic arc suite consisting of granodiorite, quartz diorite, basaltic andesite, dacite, and rhyolite (Maury et al., 1995). On the southwestern flank, in the region around the Gulf of San Miguel, it is represented by an accretionary lithofacies consisting of diabase and pillow basalt associated with radiolarian chert, named the Punta Sabana Volcanics by Bandy and Casey (1973). They recovered an assemblage of radiolarians from the interbedded chert that indicates deposition at abyssal depths during the Campanian.

Darien Formation

The middle Eocene to Oligocene Darien Formation (Fig. 2) is up to ~1500 m thick. It consists dominantly of fine and medium tuff, agglomerate, radiolarian chert, and basalt in its

lower part, and of calcareous and siliceous mudstone, micritic calcarenite, and volcanoclastics in its upper part. Radiolaria indicate mostly early to middle Eocene deposition at bathyal depths on the southwestern flank of the Chucunaque Basin (Bandy and Casey, 1973). The formation is usually faulted against or nonconformably overlies the igneous basement of the San Blas Formation and is unconformably overlain by either the Porcona or the Clarita Formation (Figs. 2 and 3).

Porcona Formation

This formation was named by Shelton (1952) the “Corcona” Formation for a tributary of the Chico River. However, since all regional maps spell the name “Porcona,” we assume that Shelton’s name is a misspelling. The Porcona Formation crops out only on the northeastern flank of the Chucunaque-Tuira Basin (Fig. 2). It consists mainly of gray and black, calcareous, foraminiferal shale, limestone, and glassy tuff with radiolarians and is between 300 and 700 m thick. It also contains probable resedimented blocks of shelly glauconitic sandstone and “orbitoid” sandstone. The unit is interpreted to

be middle-upper Oligocene and was deposited at lower bathyal depths (Esso Exploration and Production Panama, 1970).

Clarita Formation

Lithostratigraphy

The formation was named by Shelton (1952) for the Clarita River. (For details of the stratotype, reference sections, thickness, and relations with the overlying and underlying formations, see Appendix 1 and Figures DR48 and DR49.) On the northeastern flank of the Chucunaque-Tuira Basin, the Clarita Formation is generally indurated, gray-white weathering, pale blue, thick-bedded, crystalline limestone, but may range from chalky to bioclastic with occasional intercalated sandy and shaly units. In the Tuquesa River and Marraganti River sections (Fig. DR48), it has tuffaceous units interbedded in the upper 50 m. In the lower part, foraminiferal, calcareous, and tuffaceous mudstone are more abundant. On the western flank of the basin the unit becomes a fine bioclastic limestone, often with a micritic matrix, and with minor components of glauconite, feldspar, and lithic fragments. The limestone clasts may consist of up to 60% foraminifers. The formation is well bedded in units from 10 cm to 2 m and often forms prominent ridges in the field.

Biostratigraphy

The Membrillo River, Tuquesa River, and Sambu-Venado River sections provide biostratigraphic data indicating that the Clarita Formation in the area of our study ranges through the lower part of the middle Miocene (Fig. 4; Table 3). In the Membrillo River section, the lower 20 m of the exposed 30 m thick Clarita Formation belongs to (calcareous nannoplankton) zone NN4 (Fig. DR40, PPP sites 2608–2610) and (planktic foraminiferal) zone N8/M5b (PPP sites 2608 and 2609); the upper 10 m we assign to zones NN5 and N9/M6 (PPP site 2607) based on the occurrence of *Globorotalia archaeomenardii* between the HO of *Globorotalia peripheroronda* in PPP site 2606 below and the LO of *Globorotalia peripheroacuta* and *G. praefohsi* in PPP site 2611 above. In the Tuquesa River section, a sample (PPP site 1128) from near the base of the section contains microfossil assemblages typical of zones NN5 and N9/M6. In the Sambu-Venado Rivers (Fig. DR47), PPP site 2598, ~30 m above the unconformable basal contact with the San Blas Complex, yielded a planktic foraminiferal assemblage characteristic of zone N8/M5a (*Praeorbulina sicanus*, *P. transitoria*, *Globorotalia praescitula*, *Globoquadrina venezuelana*). The Clarita Formation

TABLE 3. TAXA USED TO ESTIMATE THE AGE OF THE TOP AND BOTTOM OF EACH OF THE NEOGENE FORMATIONS

	PPP sites	Age (Ma)	Calcareous nannofossils	Age (Ma)	Planktic foraminifera
Chucunaque Formation					
Top	885–887, 889, 1150–1151, 1818, 2635, 2637, 2638–2640	>7.1 – >5.6	Between LAD <i>D. hamatus</i> and LAD <i>D. quinqueramus</i>	<8.3	M13b association
Base	1612	<9.4	FAD <i>D. brouweri</i> <i>D. surculus</i>		
Membrillo River section					
Base	2630, 2650	<10.4 >9.4	<FAD <i>D. neohamatus</i> >LAD <i>D. hamatus</i>	>8.3	FAD <i>G. obliquus extremus</i>
Yaviza Formation					
	1533, 1534, 1528	>8.6 <9.4	>LAD <i>D. quinqueramus</i> < <i>D. hamatus</i>	8.3–10.9	<FAD <i>N. acostaensis</i> <FAD <i>G. obliquus extremus</i>
Tuira Formation					
Top	2605, 2577	>8.6 <9.4	LAD <i>D. hamatus</i> LAD <i>D. quinqueramus</i>	>8.3	FAD <i>G. obliquus extremus</i>
Base	902, 1132–1138	<10.4 >9.4	<FAD <i>D. neohamatus</i> LAD <i>D. hamatus</i>	10.9–11.2	<LAD <i>P. mayeri</i> >FAD <i>N. acostaensis</i>
Membrillo Formation					
Top	2526–2528	>9.4	>LAD <i>D. hamatus</i>	8.3 10.9	FAD <i>N. acostaensis</i> FAD <i>G. obliquus extremus</i>
Tapaliza Formation					
Base	2620, 2623, 2626	11.2	<FAD <i>C. coalitus</i> ?<LAD <i>D. hamatus</i>	>11.2 <11.8	<FAD <i>G. nepenthes</i> >LAD <i>P. mayeri</i>
Top	903	<10.5	<FAD <i>D. hamatus</i>	>10.5	>LAD <i>P. mayeri</i>
Base	2615, 2617	11.8	FAD <i>ID. kugleri</i>	12.8	LAD <i>G. fohsi</i>
Clarita Formation					
Top	1128, 2611	<13.6 – <15.6	>LAD <i>S. heteromorphus</i> <LAD <i>H. ampliapertura</i>	14.8	LAD <i>G. peripherocuta</i>
Base	2608–2610	<15.6	>LAD <i>H. ampliapertura</i>	16.4	<FAD <i>P. sicanus</i>

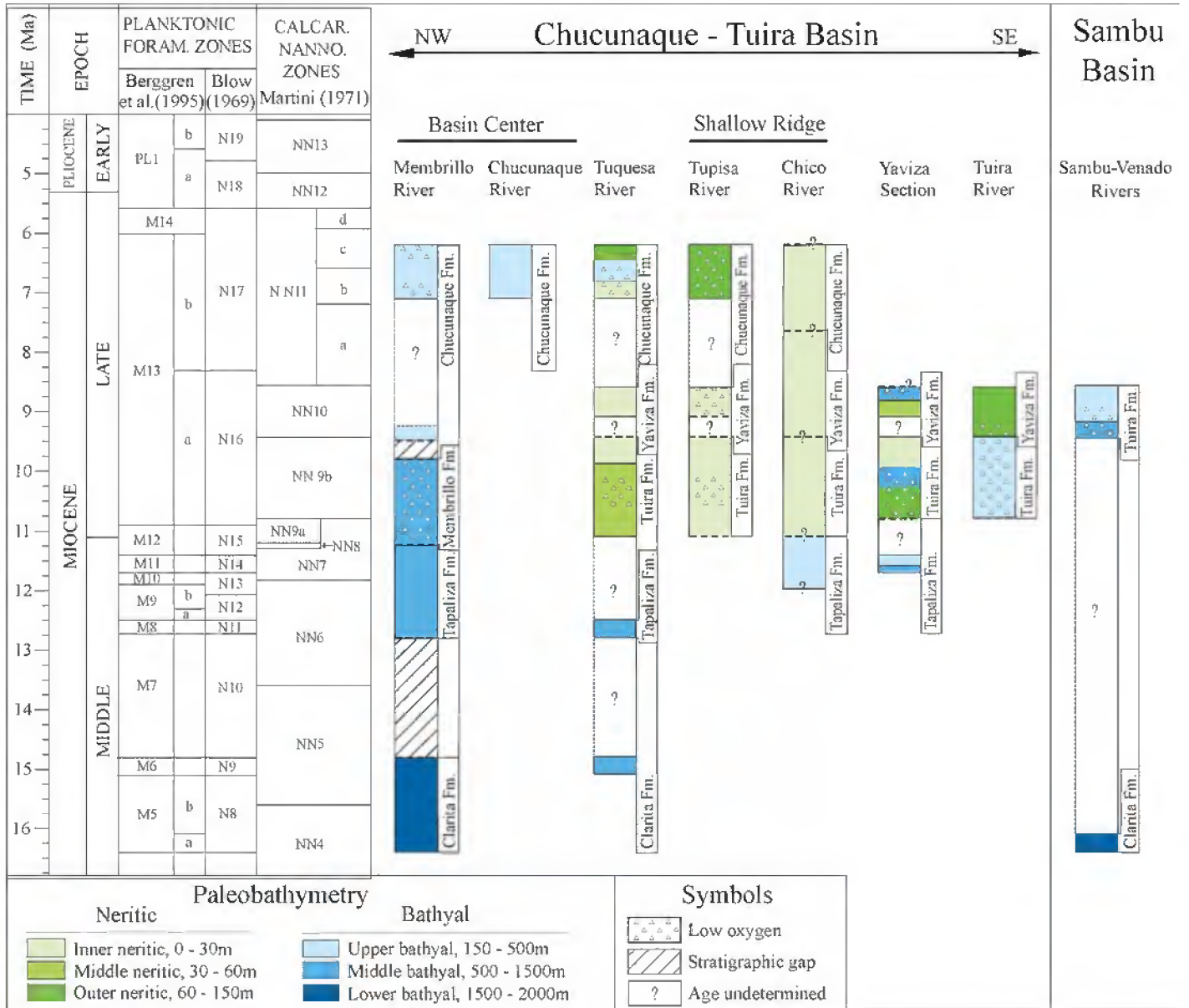


Figure 5. Paleobathymetry of Darien sections, based on benthic foraminiferal assemblages.

thus ranges from 16.4 to 14.8 Ma in this region (Fig. 4; Table 3).

Paleobathymetry

The Clarita Formation was deposited at lower to middle bathyal depths (Fig. 5). Water depth was greatest toward the center of the Chucunaque-Tuira Basin (Membrillo River section). Depths there and in the Sambu Basin were lower bathyal, 1500–2000 m. Taxa characteristic of these depths include *Cibicidoides mundulus*, *Cibicides wuellerstorfi*, *Laticarinina pauperata*, *Melonis pompilioides*, *Oridorsalis umbonatus*, and *Pullenia bulloides*. The assem-

blages resemble those of Smith’s (1964) zone F (1300–3200 m) off El Salvador, except for more endemic taxa in the latter.

Clarita Formation sediments were probably deposited at a middle bathyal depth (500–1500 m) in the Tuquesa River section. In these sediments outer neritic taxa such as *Bolivina vaughani* and *B. subexcavata* are the most abundant. However, their co-occurrence with taxa with deeper upper depth limits, such as *Hanzawaia mantaensis*, *Laticarinina pauperata*, *Rotalia garveyensis*, and rare *Cibicides wuellerstorfi* (Bandy, 1953; Bandy and Rodolfo, 1964; Smith, 1964; Ingle, 1980; van

Morkhoven et al., 1986; Finger, 1990) suggests that they have been displaced downslope to middle bathyal depths.

SYN- AND POSTCOLLISIONAL MIDDLE TO LATE MIOCENE ROCKS

We interpret the widespread regional unconformity above the Clarita Formation in the Darien province to be related to the initial collision of the Panama arc with northwestern South America and thus to separate precollisional from syn- and postcollisional rocks. The unconformity separates a dominantly open-ocean, submarine

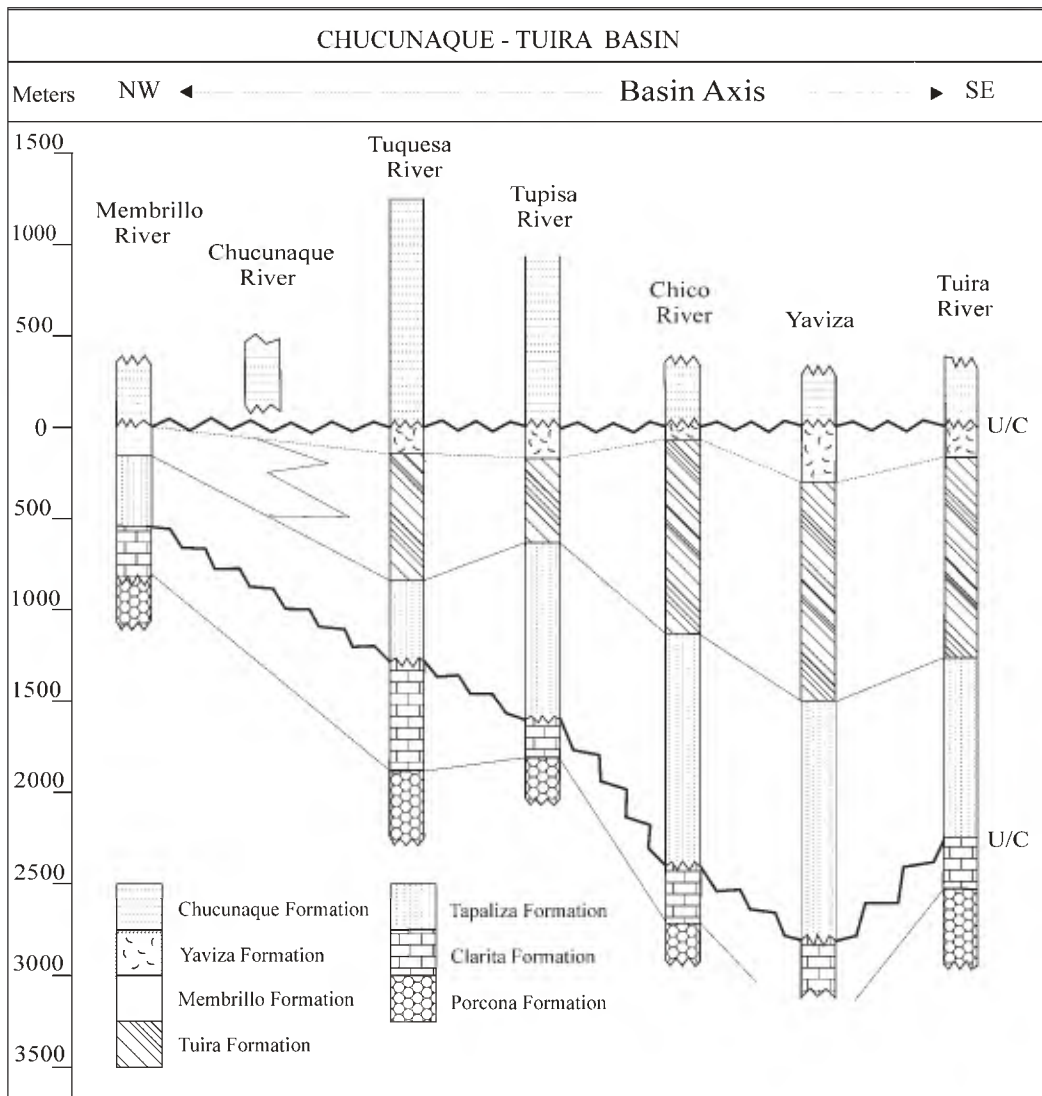


Figure 6. Lithostratigraphic correlation of Cretaceous to Miocene formations in the Darien region. See text for explanation. The two thick wavy lines represent the major regional unconformities at 14.8–12.8 and 8.6–7.1 Ma, inferred from biostratigraphic evidence and supported by abrupt lithologic changes.

volcanic and siliceous and calcareous biogenic sedimentary facies from a coarsening and shallowing upwards siliciclastic facies that suggests the proximity of a continental landmass.

Tapaliza Formation

Lithostratigraphy

The Tapaliza Formation (Esso Exploration and Production Panama, 1970) was named for the Tapaliza River, a tributary of the Tuira River. (See Appendix 1 for details of stratotype, reference sections, thickness, and stratal relations.) In the north, around the Membrillo River (Figs. 2, DR40, and DR48), the Tapaliza Formation is dominantly conchoidally weathering foraminiferal mudstone and siltstone containing abundant mollusk-rich horizons, and minor 10–20 cm thick volcanic sandstone units, often with prominent calcare-

ous 5–10 cm concretions. Occasional cobble horizons also occur.

Farther south, between the Tapaliza and Chico Rivers (Figs. 2 and DR49), the formation consists dominantly of thin, evenly bedded, coarse volcanic sandstone alternating with burrowed black shale. The base of the sandstone units is generally characterized by abundant flame structures and load casts. In the lower half of the sequence the sandstone is laminated, with low-angled cross-bedding, abundant carbonaceous material with frequent entire leaves, and concretions up to 1.5 m in diameter at some horizons. Interbedded sublaterally laminated clayey siltstone contains channel lenses with shell hash and *Pecten* shell beds.

On the western flank of the Tuira Basin, around Yaviza (Figs. 2, DR45, and DR49) the Tapaliza Formation shows a different facies. Five to 10 cm thick rhythmically bedded

turbidite units consist of alternating graded graywacke and blackish gray clayey siltstone. The siltstone units are rich in pteropods, foraminifera (especially *Orbulina*), and finely disseminated plant fragments.

Biostratigraphy

The Tapaliza Formation lies in the upper part of the middle Miocene (Fig. 4; Table 3). Microfossil assemblages were recovered at most levels sampled in the Membrillo River and Tuquesa River sections. The uppermost exposure (~2 m thick) of the Tapaliza Formation in the Membrillo River section (Fig. DR40) belongs to zone NN7 (PPP site 2617 yields the zonal marker *Discoaster kugleri*) and is in the interval between zone N12 and N14/M9–M11; PPP sites 2616–2617, based on the HO of *G. fohsi* (LAD in zone N11) at PPP site 2615 below it, a questionable occurrence of *Globoturborotalita nepenthes* (FAD in zone

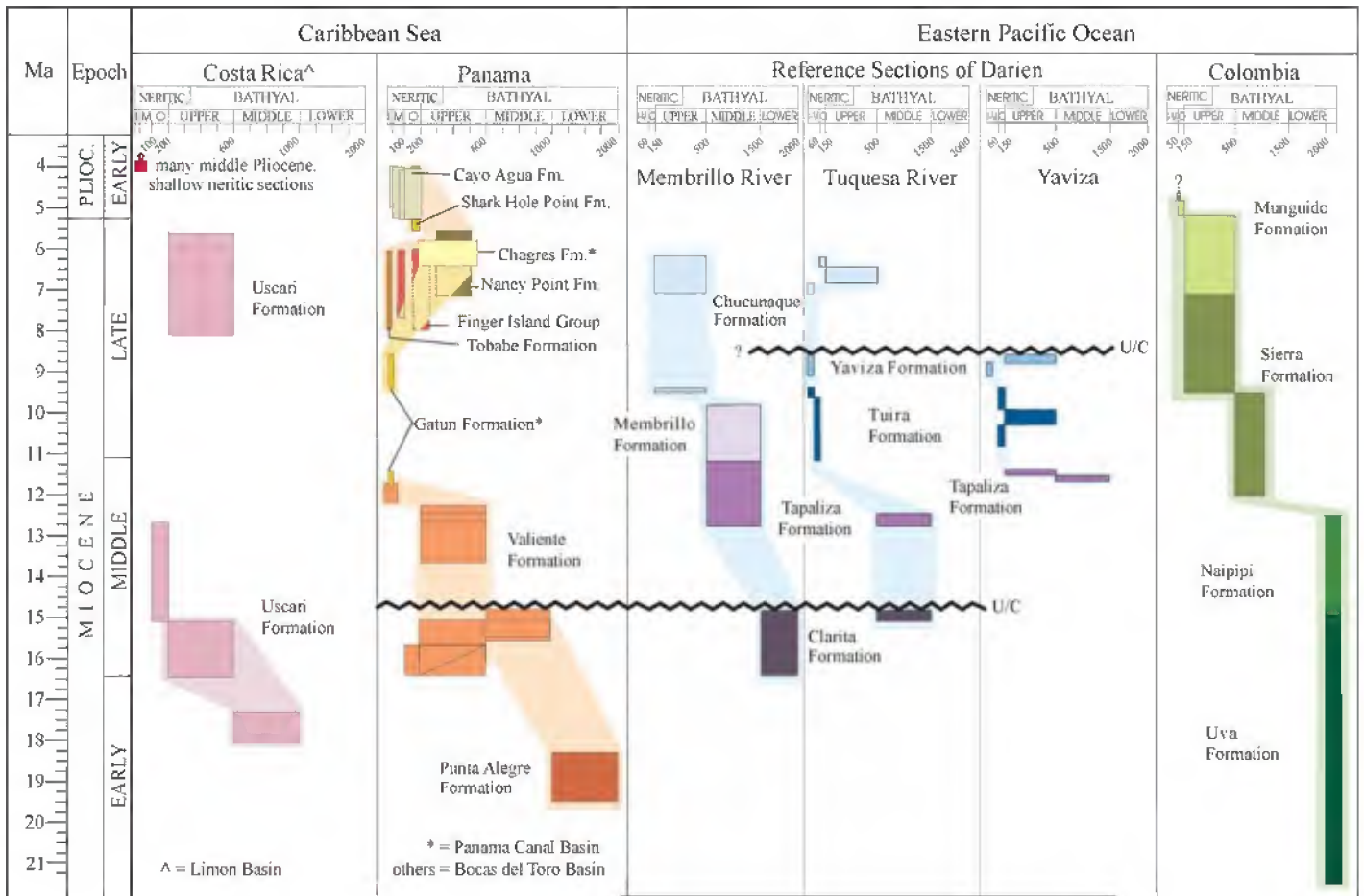


Figure 7. Stratigraphic correlation and paleobathymetry of Neogene sections of southern Central America and northwestern Colombia. Thick wavy lines represent major unconformities. Formations are differentiated by color. Shaded areas between sections denote relatively continuous geologic sections. Colombian data are based on the Opopado-1 well (Duque-Caro, 1990a; Fig. 8).

N14) at PPP site 2617, and the lowest definite occurrence of this species at PPP site 2623, 15 m above the top of the Tapaliza Formation.

The lower exposures of the formation in the Membrillo River section and its lower 10 m in the Tuquesa River section (Fig. DR42) belong to planktic foraminiferal zone N11/M8 (PPP sites 2611–2615 and 1589, respectively), characterized by the co-occurrence of *Globorotalia fohsi*, *G. praemendardii*, *G. praefohsi*, and *G. peripheroronda*.

The calcareous nannofossil assemblages in the greater part of the Tapaliza Formation in the Membrillo River and Tuquesa River sections yielded assemblages containing *Coccolithus miopelagicus*, *Discoaster deflandrei*, *D. exilis*, *D. moorei*, *D. musicus*, and *D. variabilis*, characteristic of the NN6 to NN8 zonal interval. However, since zone NN7 was definitively recognized above, the greater part of the Tapaliza Formation is constrained to zone NN6, which agrees with the planktic foraminiferal zonal determination.

The exposures of the Tapaliza Formation in the Yaviza section (Fig. DR45) are younger than in the Tuquesa River and Membrillo River sections. PPP site 904 yields well-preserved, although scarce, *Discoaster calcaris*, *D. exilis*, *D. kugleri*, and *Coccolithus miopelagicus*. Although the occurrence of the zonal marker *Catinaster coalitus* was not confirmed, this assemblage is essentially indicative of zone NN8. PPP site 903 at the top of the Tapaliza outcrop, ~30 m above PPP site 904, yielded *Discoaster hamatus*, the index species of the total range zone NN9. PPP site 903 is assigned to zones N13–N14/M10–M11 based on the occurrence of *Globorotalia druryi/nepenthes* and *P. mayeri*. The range overlap between *P. mayeri* and *D. hamatus* in the uppermost part of the Tapaliza Formation implies that it belongs to lowermost zone NN9. While the ranges of *Paragloborotalia mayeri/siakensis* and *Discoaster hamatus* do not normally overlap in Mediterranean and equatorial Atlantic and Pacific

biostratigraphies (see summaries in Berggren et al., 1995; Hilgen et al., 2000), we note that a brief stratigraphic/temporal overlap of these two taxa has been recorded in the western (Ceara Rise; Chaisson and Pearson, 1997) and eastern (Norris, 1998) equatorial Atlantic based on astrochronologically tuned time scales. The astrochronologically tuned age of the FAD of *D. hamatus* is 11.476 Ma (Hilgen et al., 2000) and the astronomically calibrated age of the FAD of *D. hamatus* in these two studies is essentially the same, but the LAD of *P. mayeri* is at ca. 10.3 Ma (suggesting a temporal extension of *P. mayeri* of ~1 m.y. at these locations). The calibration of the FAD of *D. hamatus* at ca. 10.5 Ma would appear to provide a reasonable minimum age estimate for the uppermost part of the Tapaliza Formation. The age of the base of the Tapaliza Formation (Table 3) in our study area is estimated to be ca. 12.8 Ma, corresponding to the FAD of *Globorotalia fohsi* sensu stricto (beginning of biochron M8).

Paleobathymetry

Tapaliza Formation sediments (Fig. 5) were deposited at middle bathyal depths (500–1500 m) in the deeper part of the basin (Membrillo River and Tuquesa River sections). Tapaliza Formation taxa with upper depth limits of middle bathyal along the eastern Pacific coast include *Bolivina pisciformis*, *Sphaeroidina bulboides*, *Epistominella pacifica*, and *Bulimina striata* (Smith, 1964; Ingle, 1980). Other Tapaliza Formation species characteristic of this depth include *Cibicidoides compressus* and *Hanzawaia mantaensis* (van Morkhoven et al., 1986). Near the shallow part of the basin (Chico River section), sediments of indeterminate age (that are estimated to be stratigraphically equivalent by projection of formation boundaries along strike) were deposited at upper bathyal depths, indicated by abundant *Bolivina subaenariensis* var. *mexicana* and *Uvigerina incilis* (Smith, 1964).

In the Yaviza section, seaward of the other exposures, the Tapaliza Formation at its base (PPP site 904) contains a middle bathyal fauna including *Bolivina floridana*, *Bulimina uvigerinaformis*, and *Epistominella pacifica* (Smith, 1964; Ingle, 1980). Shallowing to upper bathyal depths near the top of the formation is suggested by abundant *Bolivina* spp., *Epistominella sandiegoensis*, and *Eponides turgidus* (Smith, 1964) at PPP site 903.

Tuira Formation

Lithostratigraphy

The formation is named for the Tuira River (Esso Exploration and Production Panama, 1970). Details of the stratotype, reference sections, thickness, and stratal relations to adjacent formations are given in Appendix 1.

The formation consists of thin and regularly bedded alternations of blue gray graywacke and arkosic sandstone with dark green to black, silty claystone and siltstone. Abundant plant debris, scattered small mollusks, particularly pectinids, nuculanids, and *Notocorbula*, and abundant benthic foraminifera are typical. Many units have pervasive bioturbation or thalassinoid burrow systems. Occasional pebble breccia, shell beds, and stringers of rip-up clasts also occur. Locally, around the region of the Chico River (Figs. DR44 and DR49), shelly volcanic sandstone and pebble conglomerate, and shell beds with large, thick-shelled mollusks, are more common.

Biostratigraphy

The Tuira Formation belongs to the lower part of the upper Miocene (Fig. 4; Table 3). In the Tuquesa River section (Fig. DR42), the lower

part of the formation is assigned tentatively to the N15/M12 zonal interval. PPP sites 1132–1138 contain nondiagnostic globigerinids, globoquadrinids, and orbulinids, but the absence of *Paragloborotalia mayeri* (HO = zone N14/N15 boundary) and *Neogloboquadrina acostaensis* (LO = zone N15/N16 boundary) suggest zone N15. PPP site 1624 from the Tupisa River section (Fig. DR43) yielded scarce *N. acostaensis* (LO base N16) and *Globigerinella pseudobesa*, and PPP site 1634 yielded *Globigerinoides obliquus extremus*, placing this part of the section in zone N16/M13a (upper part) and in zone N17/M13b. In the Yaviza section (Fig. DR45), PPP site 902 yielded *Discoaster calcaris*, *D. hamatus*, and *D. neohamatus*, indicating subzone NN9b, and *N. acostaensis*, indicating zone N16/M13a (or younger).

The Tuira Formation (Fig. DR46) near the Cube River (Fig. DR49) ranges from subzone NN9b (based on the co-occurrence of *D. hamatus* and *D. neohamatus* at PPP sites 1531 and 1530) to zone NN10 (PPP site 1529, with *D. bollii*, *D. calcaris*, *D. neohamatus*, *D. prepentaradiatus*, *D. pseudovariabilis*, and *D. subsurculus*).

In the Sambu Basin (Figs. DR47 and DR50), the Tuira Formation belongs to zone N17 (partim)/M13b, based on the occurrence of *Globigerinoides obliquus extremus* (PPP site 2605 and higher) and *Globorotalia plesiotumida* (PPP site 2582 and higher). The association of *Discoaster brouweri* (PPP site 2605 and higher), *D. misconceptus*, *D. pentaradiatus*, and *D. surculus* (PPP site 2577 and higher), and the absence of *D. quinqueramus*, indicate zone NN10 (Fig. 4; Table 1), slightly older than the age determination based on planktic foraminifera. *Discoaster hamatus*, the marker for zone NN9, sporadically occurs and is clearly reworked among other Neogene taxa (e.g., *Sphenolithus heteromorphus*, *Coccolithus miopelagicus*, *Reticulofenestra floridana*, *D. petaliformis*) and Paleogene taxa (e.g., *Toweius gammation*, *Discoaster saipamensis*, *Zygrhablithus bijugatus*).

In summary, the lower part of the Tuira Formation (Table 3) cannot be assigned to a calcareous nannofossil biozone but belongs to zone N15. Its upper part belongs to subzone NN9b and zone NN10 and to zone N16–N17. The age of the formation ranges from 11.2 to 8.6 Ma. The ages of its base and top are poorly constrained by the absence of *P. mayeri* (LAD = N14/N15 biochronal boundary) and of *D. quinqueramus* (FAD = NN10/NN11 biochronal boundary).

Paleobathymetry

Sediments of the Tuira Formation were deposited at middle bathyal to inner neritic depths (Fig. 5). In the Tuquesa River section, the middle part of the exposure of the Tuira

Formation (Fig. DR42, PPP site 1137) consists of middle neritic sediments. *Hanzawaia concentrica*, extremely abundant in Smith's (1964) zone B (~30–60 m water depth), constitutes ~50% of the benthic foraminiferal fauna. Other taxa characteristic of middle neritic depths are *Amphistegina*, *Elphidium*, and *Eponides antillarum*. Shallowing to inner neritic depths (<30 m), near the top of the formation in this section (PPP sites 1602–1604), is indicated by *Ammonia beccarii* and miliolids. Sediments of the Tupisa River and Chico River sections were deposited at inner neritic depths (<30 m), as indicated by abundant *A. beccarii*, *Buliminella elegantissima*, *Elphidium* spp., *Nonionella atlantica*, and rare *Reussella atlantica* and *Uvigerina incilis*, a fauna similar to Smith's (1964) zone A (<20 m) off El Salvador.

In the southeastern Chucunaque-Tuira Basin (Tuira River and Yaviza sections) and seaward in the Sambu Basin, Tuira Formation sediments were deposited in deeper, oxygen-depleted waters. Outer neritic assemblages at the two lowest sampled horizons (PPP sites 902 and 905) of the Yaviza section include abundant *Bolivina* spp., *B. subaenariensis* var. *mexicana*, *U. incilis*, *Epistominella sandiegoensis*, and *Buliminella curta*. Although the former three taxa are also abundant at upper bathyal depths, there are no diagnostic upper bathyal elements but many neritic ones. The middle of the formation in this section (PPP site 906) contains additional deeper-water elements such as *Kleinpellia californiensis* (Finger, 1990), suggesting deepening to upper bathyal depths; the top half is barren of foraminifera, but the shelly sandstone lithology suggests an inner neritic lithology. The Tuira Formation exposed in the Tuira River section has a similar fauna but includes bathyal *Bulimina uvigerinaformis* and *Bolivina hootsi*. All of these bathyal to outer neritic assemblages lived in oxygen-depleted waters, as indicated by their low diversity ($\alpha = 2$ to 5) and relatively small, thin-walled tests.

The Tuira Formation of the Sambu Basin contains an upper middle bathyal assemblage (Fig. 5) at its lowest sampled horizon (Fig. DR47, PPP site 2605), with abundant *Bulimina uvigerinaformis* and *Concavella gyrooidinaformis*, both having upper bathyal depth limits (Ingle, 1980; Resig, 1990; Finger, 1990). This is an originally low-diversity assemblage that was supplemented with transported, middle to outer neritic taxa (see evidence for massive reworking in nannofossil assemblages under "Biostratigraphy" above). Depths shallowed to upper bathyal higher in the section (PPP sites 2582 and 2577), as indicated by *Bolivina subaenariensis* var. *mexicana*, *Bolivina pisciformis*, *Suggrunda eckisi*, and *Uvigerina*

incilis, all in Smith's (1964) zone D biofacies (150–600 m) off El Salvador.

Membrillo Formation

Lithostratigraphy

We name this formation for the Membrillo River. Details of the stratotype, thickness, and stratal relations are given in Appendix 1. The base of the Membrillo Formation denotes the transition from the coarser thicker sediments of the shallow zone of the Chucunaque-Tuira Basin around the Chico and Tupisa Rivers region, westward into finer-grained (and deeper-water) deposits of the Bayano Basin (Fig. 2). The Membrillo Formation is the lateral equivalent of the Tuira Formation. It consists mainly of blue gray, conchoidally fracturing, blocky and shelly mudstone with abundant slabby concretions in the upper portion. In the lower portion, there are frequent mollusk shell beds, 20 cm thick sandstone units, and occasional volcanic cobble horizons.

Biostratigraphy

We tentatively assign the Membrillo Formation to the lowest part of the upper Miocene (Fig. 4; Table 3). The lower part of the formation (Fig. DR40, PPP sites 2619, 2621 and 2622) probably lies in the NN7–NN8 and N13–N14 zonal intervals. PPP site 2620, ~40 m above the base of the formation, yielded a single typical specimen of *Catinaster coalitus* (marker of the base of zone NN8), *Discoaster calcaris*, and a five-rayed discoaster tentatively assigned to *D. hamatus* (whose range defines zone NN9); it is assigned to zone NN8 or NN9. The interval between PPP site 2623 (LO of *Globoturbotalita nepenthes*) and PPP site 2626 (HO of *Paragloborotalia mayeri*) belongs to zone N14/M11. PPP site 2628 (which includes the LO of *N. acostaensis*) is in zone N16. The intervening PPP site 2627 is assigned to zone N15/M12. *Discoaster hamatus* occurs at PPP sites 2625, 2627, and 2628, indicating zone NN9. Discoasters other than *D. hamatus* are very rare in this interval, so it is not possible to rely on the absence of *D. neohamatus* to characterize subzone NN9a. However, foraminiferal correlation of this interval with zones N14 to N16 essentially supports assignment to the lower part of zone NN9. Although the ranges of *P. mayeri* and *D. hamatus* do not overlap in the time scale of Berggren et al., 1995, they co-occur in PPP sites 2626 and 2625. However, extensive reworking of Paleogene (e.g., *Reticulofenestra bisecta*, *Coccolithus eopelagicus*, *Discoaster saipanensis*) and Neogene (e.g., *D. deflandrei*, *R. floridana*) taxa in these sites may indicate that *P. mayeri* is also reworked, accounting for the overlap with *D. hamatus* (but see discussion above).

The temporal extent of the Membrillo Formation is difficult to establish because the biostratigraphic location of its base and top are poorly constrained. However, considering the (NN7/N12–N14) zonal position of the upper part of the underlying Tapaliza Formation, it can only lie in zones NN7–NN8/N12–N14. The evidence cited above shows that the Membrillo Formation spans zones NN8 and NN9 (partim), and zones N14, N15, and N16 (partim). We tentatively conclude (Table 3) that it extends from latest biochron NN7 to mid zone NN9, i.e., >11.2 to >9.4 Ma.

Paleobathymetry

Sediments of the Membrillo Formation were deposited under middle bathyal (500–1500 m), oxygen-deficient conditions (Fig. 5). Whereas many of the benthic foraminiferal taxa are most abundant at upper bathyal depths (e.g., *Bolivina imporata*, *B. subaenariensis* var. *mexicana*, *Cibicorbis hitchcockae*), the deepest-dwelling species, *Epistominella pacifica* (up to 36% of the assemblage), *Bolivina pisciformis*, and *Bulimina uvigerinaformis* are characteristic of middle bathyal depths (Smith, 1964; Ingle, 1980). The diversity at PPP site 2619 (Fig. DR40) is low ($\alpha = 5.5$), suggesting a low oxygen level.

Yaviza Formation

Lithology

The Yaviza Formation is newly defined and named for the town of Yaviza, the eastern terminus of the Pan-American Highway (Fig. DR49). Details of the stratotype, reference sections, thickness, and stratal relations are given in Appendix 1. The Yaviza Formation consists mainly of blue gray, massively bedded, pervasively bioturbated, shelly, lithic sandstone. Oyster beds, ledging calcified hard beds, and irregular large concretions are scattered throughout. Abundant whole mollusks, sometimes forming shell beds, and dense shell hash are also distinctive. The uppermost part of the formation is characterized by coquinooid limestone units and densely packed, hard, shelly sandstone with shells often concentrated in burrows. Some shell beds are oyster banks, and others have large bivalves. The Yaviza Formation crops out in the central and eastern Chucunaque-Tuira Basin but thins westward and is not present in the Membrillo River section and beyond (Fig. 2).

Biostratigraphy

The Yaviza Formation (Fig. 4; Table 3) is placed in the middle part of the upper Miocene, based on the evidence from the upper Tuira River section (Fig. DR46). PPP sites 1533 and 1534 (Fig. DR50) yielded *Discoaster bollii*

(LAD in biochron NN10); *D. neohamatus*, cf. *D. calcaris* and *D. surculus* (FAD in biochron NN10), occur at PPP site 1534. The absence of *D. hamatus* and the presence of *D. surculus* allow confident assignment to zone NN10 (Fig. 4). In corroboration, the presence of *Neogloboquadrina acostaensis* and the absence of *Globigerinoides obliquus extremus* (which occurs sporadically in the overlying Chucunaque Formation elsewhere) at PPP site 1528, ~6 m below PPP sites 1533–1534, indicates zone N16/M13a. This implies that the Yaviza Formation falls within a 0.8 m.y. interval between 9.4 and 8.6 Ma (Table 3).

Paleobathymetry

The Yaviza Formation is an inner neritic deposit. Benthic foraminifera are generally absent from the Tuquesa River, Tupisa River, and Chico River sections (Fig. 5) or are very poorly preserved; however, abundant *Nonionella atlantica*, *Ammonia beccarii*, and *Elphidium* spp. were identified at PPP site 1609 (Fig. DR42), PPP sites 1144–1146, PPP site 1149 (Fig. DR43), PPP site 1563 (Fig. DR44), and PPP site 1569 (Fig. DR44). These are predominantly inner neritic species from depths <25 m off Panama (Golik and Phleger, 1977) and El Salvador (Smith, 1964).

The Yaviza Formation near Yaviza (Figs. 5, DR45, and DR48) appears to be a slightly deeper, middle neritic facies. The inner neritic taxa mentioned above are less common, and species that live mostly deeper than 30 m, such as *Bolivina vaughani* and *Hanzawaia concentrica*, are very abundant. Farther south, near the Cube River (Fig. DR48), the Yaviza Formation (Fig. DR46) is an outer neritic facies. It contains abundant *Epistominella sandiegoensis* (characteristic of outer neritic assemblages off El Salvador) and *Bolivina subaenariensis* var. *mexicana*, indicative of outer neritic to upper bathyal depths (Smith, 1964).

At the top of the Yaviza Formation near Yaviza (Figs. DR45 and DR50), there is an anomalous occurrence of an upper bathyal assemblage at PPP site 912. This assemblage includes upper bathyal indicator taxa such as *Cibicoides colombianus*, abundant in the upper bathyal Chagres Formation of the Panama Canal Basin (Collins et al., 1996a), and *Bulimina uvigerinaformis*, abundant in the Tapaliza Formation.

Chucunaque Formation

Lithostratigraphy

The formation was named for the Chucunaque River by Shelton (1952). Details of the stratotype, reference sections, thickness, and stratal relations are given in Appendix 1. The

Chucunaque Formation consists of gray weathering, greenish blue to black, blocky to massive, silty claystone and siltstone, with minor thin horizons and stringers of volcanic sandstone. Slabby to oval calcareous concretions are common, and the formation contains abundant gypsum crystals at some horizons. Calcified thalassinoid burrows are typical and many levels are packed with clearly visible foraminifera, scattered small mollusks, including cancellariids, naticids, *Tellina*, and turrids. Crabs, pteropods and the deepwater *Pecten* and *Palliolium* have also been observed. In the north, along the Membrillo River (Fig. DR40), the lower part of the formation is dominated by cobble conglomerate and cross-bedded sandstone.

Biostratigraphy

Over most of its outcrop the Chucunaque Formation is upper Miocene and belongs to zone NN11 and possibly NN10, and to zone N17/M13b and possibly N16 (M13a; Fig. 4; Table 3). The upper part of the Chucunaque Formation in the Membrillo River (Fig. DR40, PPP sites 2635 and 2637), in the Tuquesa River (Fig. DR42, PPP sites 887–889 and 1616), in the Tupisa River (Fig. DR43, PPP sites 1150 and 1151), and in the Chucunaque River (Fig. DR41, PPP sites 885, 886, and 2638 to 2640) sections belongs to zone NN11. Assemblages are characterized by the zonal marker *Discoaster quinqueramus*. The absence of *D. neohamatus* in these assemblages suggests levels younger than subzone NN11a, this species being common in older formations of the Darien province. The Chucunaque Formation contains foraminiferal assemblages in the Membrillo River (PPP sites 2631, 2635, and 2637), the Tuquesa River (PPP sites 1616, 1615, 887, and 888), and the Tupisa River (PPP sites 1150 and 1151) sections that yielded an association of *Neogloboquadrina acostaensis* and *Globigerinoides obliquus extremus*, characteristic of the upper Miocene zone N17(partim)/M13b.

The age of the lower part of the Chucunaque Formation in different sections is poorly constrained within the NN10–NN11 zonal interval, in part because of the small number of samples available for dating. PPP site 2641 at the base of the Chucunaque River section (Fig. DR41) yielded only scarce, long-ranging nannofossils. The Tuquesa River section PPP site 1612 (Fig. DR42) yielded very rare nannofossil taxa and extremely rare discoasters including *Discoaster brouweri* and *D. surculus*. The absence of *D. quinqueramus* could be interpreted as indicative of zone NN10. However, there is no positive evidence (e.g., occurrence of *D. bollii*) in support of such a zonal assignment, and *D. quinqueramus* was not encountered at all levels in the interval clearly assignable to zone NN11.

In the Membrillo River section (Fig. DR40), the base of the Chucunaque Formation may be older than elsewhere in the Chucunaque-Tuira Basin. PPP site 2630, ~90 m above the base of the formation, yields a peculiar assemblage in which discoasters predominate over other nannofossils. This assemblage is characteristic of subzone NN9b (Fig. 4) based on the co-occurrence of *D. hamatus* and *D. neohamatus*, and supported by the presence of *D. bollii* and *D. calcaris*. No species that would characterize a younger zone (e.g., *D. brouweri*, *D. pentaradiatus*, *D. surculus*) were encountered, but well-preserved specimens of *D. petaliformis* (NN4–NN5 zonal range) occur, indicating reworking. Assignment to planktic foraminiferal zone N16/subzone M13a (based on an association of *Globigerinella pseudobesa*, *Gl. aequilateralis*, *Globigerinoides obliquus*, *G. ruber*, *Orbulina suturalis*, *Globigerina bulloides*, *Neogloboquadrina acostaensis*, and the absence of *Globigerinoides obliquus extremus*) would support a zonal assignment older than zone NN11.

In summary, the age span of the Chucunaque Formation in most of the Chucunaque-Tuira Basin can be broadly estimated as ca. 7.1 Ma to ca. 5.6 Ma (Table 3). The 5.6 Ma estimate for the upper limit of the formation corresponds to the LAD of *D. quinqueramus* (NN11/NN12 zonal boundary). The 7.1 Ma estimate corresponds to the LAD of *D. neohamatus* (NN11a/NN11b subbiochronal boundary). To the north, where the Chucunaque Basin changes over to the Bayano Basin, the base of the Chucunaque, with a calcareous nannofossil assemblage of subzone NN9b, appears to be older than 9.4 Ma (Fig. 4).

Paleobathymetry

The Chucunaque Formation (Fig. 5) was deposited at an inner neritic depth around the Chico River valley region (Fig. DR44), and at upper bathyal depths in deeper portions of the basin (Membrillo River section; Fig. DR40). It commonly contains oxygen-deficient assemblages. In the Membrillo River and Chucunaque River sections, samples contain characteristic upper bathyal taxa such as *Bolivina acuminata*, *B. hootsi*, *B. subaenariensis* var. *mexicana*, *Planulina ornata*, and *Uvigerina marksii* (Smith, 1964; Ingle, 1980; Whittaker, 1988). Diversity ranges from $\alpha = 5.5$ (Membrillo River section), which indicates low-oxygen stressed assemblages, to 15 (Chucunaque River section), which indicates normal, oxygenated conditions. These values suggest that deposition of the Chucunaque Formation occurred in oxygen-deficient waters at different times and places.

In the Tuquesa River (Fig. DR42), the Chucunaque Formation has several facies (Fig. 5).

Abundant *Ammonia beccarii* and *Nonionella* near the base (PPP sites 1611 and 1612) indicate inner neritic depths that are also reflected in the silty, sandy limestone lithofacies. In the middle of the formation (PPP site 1616), a low-diversity assemblage dominated by *Uvigerina incilis* with abundant *Bolivina acuminata* is most similar to Smith's (1964) upper bathyal facies, and low diversity indicates low oxygen. Near the top (PPP site 888), an upper bathyal / outer neritic depth is indicated by abundant *U. incilis*, *B. acuminata*, *Cassidulina laevigata*, and *Epistominella sandiegoensis*. At the top (PPP site 891), a diverse outer neritic assemblage including *Amphistegina* and *Eponides antillarum* suggests normal oxygenation and nearby carbonate shoals.

PPP site 1150 from the upper part of the Chucunaque Formation exposed in the Tupisa River (Fig. DR43) contains a low-diversity ($\alpha = 4$) outer neritic assemblage dominated by *Epistominella sandiegoensis*, *Bolivina subaenariensis* var. *mexicana*, and *B. acuminata*. This indicates a deepening from the inner neritic facies of the underlying Yaviza Formation.

Benthic foraminiferal assemblages from the Chucunaque Formation (Fig. 5) in the Lower Chico River section (which lacks age control) include *Buccella* sp., *Buliminella elegantissima*, *Elphidium* sp., and *Nonionella atlantica*. These are predominantly inner neritic taxa (Golik and Phleger, 1977), although the absence of the predominantly nearshore species *Ammonia beccarii* suggests the deep end of that estimate.

REGIONAL UNCONFORMITIES

Limited exposures in some regions and poor preservation in others resulted in unevenly spaced samples, so we were able only to establish the biozonal position of particular stratigraphic intervals within sections. Lithostratigraphic correlation of the eight sections (Fig. 6) shows that the Tapaliza and Tuira (plus Membrillo) Formations thicken and coarsen from the deeper part of the basin in the Membrillo River section toward Yaviza (Chico River and Yaviza sections), the site of active deltaic deposition during the late Neogene. Two regional unconformities (shown by thick wavy lines on Figs. 4 and 6), inferred from biostratigraphy, occur (1) between the Clarita and Tapaliza Formations and (2) between the Yaviza and Chucunaque Formations. The contact between the Clarita Formation (M5b–NN5) and Tapaliza Formation (M8–NN6) in the Membrillo River section is unconformable, with a hiatus estimated at ~2 m.y. (Fig. 4) from middle middle to late middle Miocene (14.8–12.8 Ma). The base of the Tapaliza Formation in the Tuquesa River

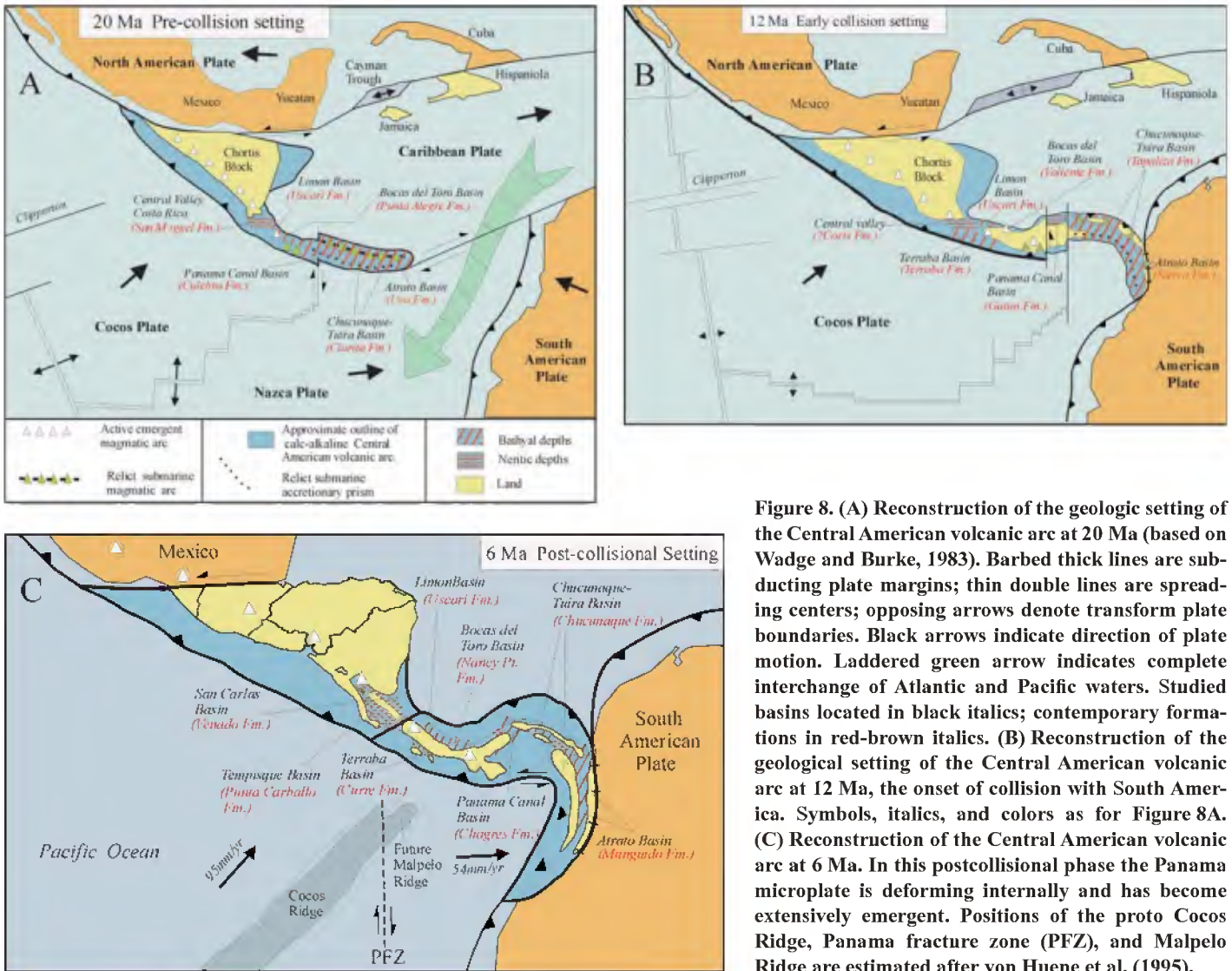


Figure 8. (A) Reconstruction of the geologic setting of the Central American volcanic arc at 20 Ma (based on Wadge and Burke, 1983). Barbed thick lines are subducting plate margins; thin double lines are spreading centers; opposing arrows denote transform plate boundaries. Black arrows indicate direction of plate motion. Laddered green arrow indicates complete interchange of Atlantic and Pacific waters. Studied basins located in black italics; contemporary formations in red-brown italics. (B) Reconstruction of the geological setting of the Central American volcanic arc at 12 Ma, the onset of collision with South America. Symbols, italics, and colors as for Figure 8A. (C) Reconstruction of the Central American volcanic arc at 6 Ma. In this postcollisional phase the Panama microplate is deforming internally and has become extensively emergent. Positions of the proto Cocos Ridge, Panama fracture zone (PFZ), and Malpelo Ridge are estimated after von Huene et al. (1995).

section is the same age, and although the top of the Clarita Formation is less well constrained, a similar hiatus probably also exists.

The younger regional unconformity (Yaviza/Chucunaque contact) is defined by the top (NN10; 9.4–8.6 Ma) of the middle late Miocene Yaviza Formation in the Tuira River section, and the overlying latest Miocene Chucunaque Formation (zone NN11-M13b), whose age is less precisely constrained over most of the basin at 7.1 Ma (Fig. 4).

These biostratigraphically inferred unconformities (Fig. 4) can be related to the collisional events. Across the Clarita/Tapaliza unconformity (14.8–12.8 Ma) there is a change from a deepwater, pelagic, nonsiliciclastic facies to a shallower, higher-energy, siliciclastic facies, evidence that collision of the Panama arc with South America had now interrupted deepwater

Caribbean–eastern Pacific circulation. The Yaviza/Chucunaque unconformity (8.6–7.1 Ma) is marked by a hiatus after the widespread deposition of oyster reefs, coquinoïd limestone, pebble conglomerate, and shelly sandstone. This widespread distribution of inner neritic facies is evidence of uplift caused by continued shortening and uplift from the completed docking of the southern Central American isthmus with South America. A similar pattern in correlative deposits of the Panama Canal and Bocas del Toro Basins is evidence that these effects extended (Fig. 7) at least as far as western Panama.

A subsequent probable eustatic deepening pulse is reported in the Chucunaque Formation overlying the Yaviza/Chucunaque unconformity, also observed in the Panama Canal and Bocas del Toro Basins. This event preceded regional uplift and final emergence in the Darien

region of the Central American Isthmus in the earliest Pliocene.

GEOLOGIC HISTORY

Precollisional Events

The oldest record of the Central American arc in the Darien is the Upper Cretaceous San Blas Complex (Basement Complex of Bandy and Casey, 1973), composed of intrusive igneous rocks in the San Blas and Darien Massifs, and pillow basalt, radiolarian chert, tuff, and agglomerate (Fig. 2) in the Mahé, Pirre, and Sapó Massifs. Maury et al. (1995) identify a Paleocene–early Eocene volcanic arc from sections in central Panama at Sona and the Azuero Peninsula, offset northward by a series of left-lateral faults (Fig. 8A). The most important of these

is the Panama Canal Zone fault, east of which the Paleocene–Eocene arc continues in the San Blas and Darien Massifs of the Darien. These rocks represent early subduction of the Farallon plate along the western margin of the Caribbean plate during the Upper Cretaceous to lower Eocene, when the Panama arc lay to the west of South America (Wadge and Burke, 1983).

Separated from the San Blas Complex by a hiatus, the overlying middle Eocene to upper Oligocene Darien Formation (Morti Tuffs of Bandy and Casey, 1973) records continued abyssal deposition of basalt, agglomerate, tuff, and volcanoclastics. In the Mahé Massif, the Darien Formation ranges higher into the Oligocene and possibly lowest Miocene in a continued deepwater facies of volcanoclastics, radiolarian chert, and tuff (Pacific Tuffs of Bandy, 1970; Bandy and Casey, 1973). In the San Blas and Darien Massifs, the Darien Formation is replaced in the Oligocene by the Porcona Formation, which consists of calcareous mudstone, sandstone, limestone, and tuff, also rich in radiolarians. These deepwater facies contain frequent records of probable slumped blocks, e.g., “orbitoid” sandstone with pectenids (Shelton, 1952, p. 21), which are similar to large-scale contemporaneous slumped units in the Bayano Basin to the west (Stewart, 1966, p. 12) and the Dabeiba and Baudo arches of Colombia (Duque-Caro, 1990b). These sequences are capped throughout the Darien by the lower middle Miocene Clarita Formation. The San Blas Complex, Darien Formation, and Porcona Formation record the early submarine history of the southern Central American volcanic arc prior to its middle Miocene docking with South America (Fig. 8A).

The Darien region of Panama and the Atrato Basin of Colombia (Duque-Caro, 1990a, 1990b) form the eastern portion of the Central American volcanic arc that collided with the northwestern corner of South America to create the Isthmus of Panama (Fig. 8B). Different plate-tectonic models have proposed that the collision occurred between ca. 10 and 20 Ma (Wadge and Burke, 1983; Kellogg and Vega, 1995; Mann and Kolarisky, 1995; Trenkamp et al., 2002). Our data suggest that initial collision and docking took place from ca. 12.8 to 9.5 Ma.

The Central American volcanic arc appears to have risen and become more emergent by ~16 Ma, before collision (Fig. 7), as evidenced by shallowing from lower and middle to upper bathyal and outer neritic depths in the southern Limon and Bocas del Toro Basins. However, the Clarita and Uva Formations (Duque-Caro, 1990a) of the Darien and the Atrato Valley, respectively, remained lower bathyal to abyssal at this time, suggesting a significant oceanic

gap between Central America and South America (Fig. 8A).

Syn- and Postcollisional Events

Syncollisional events are reflected in the shallowing of the Chucunaque-Tuira Basin from middle to upper bathyal depths, as recorded by the upper middle Miocene Tapaliza Formation (Figs. 5 and 8B). Pacific middle bathyal benthic foraminifera of the Atrato Basin lost their Caribbean affinity at this time (Duque-Caro, 1990a). From 11.2 to 9.4 Ma, bathyal sedimentation continued in the deepest part of the Chucunaque-Tuira Basin (Membrillo Formation), but southward to the Yaviza area, depths shallowed to neritic (Tuira Formation). Major shallowing in the Atrato Valley began at ca. 12 Ma (Fig. 7). By 9.4 Ma all regions of the Darien and the Atrato Valley had shallowed to inner neritic to upper bathyal depths. For these sediments Duque-Caro (1990a) proposed deposition in inner borderland basins. Similarly, shallowing had also occurred in the Panama Canal and Bocas del Toro Basins of central and western Panama (Fig. 7). Coccolith biotas (Roth et al., 2000) became differentiated at this time, and the first exchange of terrestrial faunas (raccoons migrating to the south and ground sloths to the north) between North and South America occurred at 9.3–8.0 Ma (Marshall et al., 1979; Marshall, 1985; Webb, 1985). We therefore suggest 12.8–9.5 Ma is the period of initial collision of the Central American arc with South America. The culmination of this collisional phase appears to be represented by a hiatus of up to 1.5 m.y. that occurred across most of the Darien region (Figs. 4 and 7). It ranges between the top of the shelly, oyster reefal Yaviza Formation, dated at 8.6 Ma, and the base of the Chucunaque Formation (7.1 Ma), except in the Membrillo River area, where it is represented by a cobble conglomerate, presumably deposited in very shallow water.

Postcollisional events in the Darien (Fig. 8C) include the deposition of the Chucunaque Formation in upper bathyal depths in the northwest of the Chucunaque-Tuira Basin and at mostly neritic depths to the southeast, until 5.6 Ma. No Pliocene deposits have been recorded in the Darien, which was by then presumably emergent. In the Atrato Valley (Fig. 7), the Sierra and Munguido Formations were deposited at upper bathyal depths and then shallowed to neritic in the Pliocene (Fig. 7), although no deposits younger than 4.8 Ma are recorded (Duque-Caro, 1990a).

The latest definitive episode of Pacific-Atlantic connection occurred ca. 6 Ma in the Panama Canal Basin (Fig. 8C), where the inner neritic Gatun Formation is overlain by the upper bathyal

Chagres Formation, which contains a diverse benthic foraminiferal fauna of otherwise exclusively Pacific affinity (Collins et al., 1996a). This deepening pulse can be correlated (Fig. 7) with similar paleobathymetric transitions in the Bocas del Toro Basin from the inner neritic Tobabe Sandstone to the upper bathyal Nancy Point Formation (Coates et al., 2003), and in the Limon Basin of Costa Rica from neritic to upper bathyal within the Uscari Formation (Cassell and Sen Gupta, 1989; Collins et al., 1995). It is also reflected in the Darien region by a transition from inner neritic to outer neritic / upper bathyal within the Yaviza Formation in the region of the Tupisa and Tuquesa Rivers. The nature of this event is almost certainly eustatic rather than tectonic, given its regional scope, and it may correspond to a sea-level rise at ca. 6 Ma (Haq et al., 1987; Billups and Schrag, 2002). Around this same time, Caribbean reef corals and carbonate-associated benthic foraminifera experienced increased diversification (Collins et al., 1996b). Outer neritic benthic foraminifera of the eastern Pacific (Ecuador) show developing endemism in relation to Caribbean faunas, but middle neritic faunas, which should have been less affected by the rising sill, show less endemism (Schultz and Collins, 2002).

Shortening of the central Chucunaque-Tuira, Sambu, and Bayano basins, as well as structures in the Gulf of Panama (Mann and Kolarisky, 1995), involve all Neogene units as young as 5.6 Ma. Postcollisional deposition may have originally been in elongate narrow borderland basins with a highland source immediately to the northwest of the area of the Tuquesa River to Chico River valleys, where thicker, coarse deltaics are well developed. Lower Pliocene folding of the Chucunaque-Tuira Basin and Bayano Basin sediments, in response to early Pliocene shortening, was followed by formation of a series of doubly plunging or truncated en echelon folds along the southern margin of the Chucunaque-Tuira Basin, subsequently cut off to the south by the Sanson Hills left-lateral strike-slip fault (Wing and MacDonald, 1973; Mann and Kolarisky, 1995; Fig. 2). In the southeast of the Chucunaque-Tuira Basin, the Sanson Hills fault and en echelon folds are abruptly terminated by the northeast-trending Pirre fault, an apparently eastward-dipping, high-angle reverse thrust.

These structures, together with the NW-SE-trending Jaque River fault, and the Sambu and Mahé faults (Fig. 2), postdate the Chucunaque Formation (5.6 Ma). They are correlated with the formation of a postcollision Panama microplate (Fig. 1) that was detached from the Caribbean plate in the north by the convergent North Panama deformed belt (Adamek et al., 1988) and from the Nazca plate to the south

by the South Panama deformed belt (Mann and Kolarsky, 1995). However, undeformed ?late Pliocene–Pleistocene sediments bury deformed older Neogene sediments in the East Panama deformed belt and the western Gulf of Panama and Pearl Island Basins (Mann and Kolarsky, 1995). Furthermore, Kellogg and Vega (1995) and Trenkamp et al. (2002), using global positioning system measurements, have indicated that the Panama microplate is now acting as a rigid indenter with respect to South America. This suggests that the main phase of shortening and internal deformation of the Panama microplate was concentrated after 5.6 Ma, in the early Pliocene, but had strongly diminished or ceased by late Pliocene–Pleistocene time. The Darien faults manifest intraplate Pliocene deformation by northwest-oriented left-lateral strike slip (Mann and Corrigan, 1990; Mann and Kolarsky, 1995). The Panama microplate has been interpreted (Mann and Burke, 1984; Burke and Şengör, 1986; Stephan et al., 1986; Mann and Kolarsky, 1995) as an example of northwestward “escape” of fault-bounded blocks involved in the ongoing collision of South America with the Caribbean plate.

CONCLUSIONS

1. Prior to the collision of the southern Central American arc with South America, Upper Cretaceous to lower middle Miocene rocks of the San Blas Complex, and the Darien, Porcona, and Clarita Formations, were deposited in abyssal to lower bathyal depths in an open-ocean, low-energy, essentially nonsiliciclastic sedimentary environment distant from South America. Similar environments have been recorded from the Atrato Basin of northwestern Colombia (Lower-middle Miocene Uva and Naipipi Formations) and the Bocas del Toro Basin of western Panama (lower Miocene Punta Alegre Formation).

2. Syn- and postcollisional geologic history is represented in the Darien region by a shallowing and coarsening upward sequence in the Neogene. In the Chucunaque-Tuira Basin the sequence is divided into five formations as follows: the upper middle Miocene Tapaliza Formation (middle-upper bathyal, volcanic sandstone and turbidites); the lower upper Miocene Tuira and Membrillo Formations (mostly low-oxygen, upper bathyal / middle neritic, shelly, fine to coarse volcanoclastics); the middle upper Miocene Yaviza Formation (inner-middle neritic, bioturbated shelly sandstone, and coquinoid limestone with oyster beds); and the middle to upper Miocene Chucunaque Formation (low-oxygen, upper bathyal / inner neritic, foraminiferal mudstone and cross-bedded sandstone and conglomerate).

3. The pre- and postcollisional sequences are separated by a regional unconformity from 14.8 to 12.8 Ma. This hiatus is also present in the Bocas del Toro Basin. The hiatus signals the end of mainly pelagic, nonsiliciclastic, abyssal to lower bathyal sedimentation in the region and the beginning of the collision of the southern Central American arc and South America.

4. Following the hiatus, a sequence of middle Miocene to middle upper Miocene rocks (Tapaliza, Tuira, and Membrillo Formations) record regional shallowing from bathyal to neritic depths from 12.8 to 9.5 Ma, which corresponds to the initial docking of the Panama arc with South America. This also coincides with the rise and emergence of the volcanic arc in the Panama Canal Basin (Gatun Formation) and Bocas del Toro Basin (Valiente Formation), and shallowing from middle bathyal to neritic depths in the southern Limon Basin (Uscari Formation). Other probable consequences of the collision are a “carbonate crash” in the Caribbean, following North Atlantic Deep Water strengthening, divergence of the Pacific and Caribbean coccolith and benthic foraminiferal faunas, diversification of reef corals and reef-associated benthic foraminifera, and the first terrestrial faunal interchange between North and South America.

5. Coquinoid limestone and oyster banks of the neritic Yaviza Formation (9.4–8.6 Ma), and the 1.5 m.y. hiatus at the top of the Yaviza Formation, suggest that much of the Darien region was emergent by ca. 8.6 Ma. Postcollisional deposition (Chucunaque Formation) was probably in narrow borderland basins and ceased by 5.6 Ma in the Darien and 4.8 Ma in the Atrato Valley.

6. A eustatic sea-level rise occurred near the top of the Chucunaque Formation (ca. 7–6 Ma) that correlates with those observed in the Bocas del Toro, Panama Canal, and Limon Basins. It was enough to breach the isthmus in the Panama Canal Basin and locally bring Pacific faunas to the Caribbean.

7. After 5.6 Ma, the elongated Bayano-Chucunaque-Tuira syncline was formed by shortening within the detached Panama microplate defined by its convergent boundaries to the north (North Panama deformed belt) and south (South Panama deformed belt). Continued intraplate deformation produced multiple en echelon doubly plunging and truncated folds along the southern margin of the syncline that were subsequently truncated by left-lateral, strike-slip movement along the Sanson Hills fault. Similar movement along several faults in the Darien region indicates that internal deformation of the Panama microplate was by northwestward “escape” of fault-bounded segments.

8. Unfolded and unfaulted ?late Pliocene–Pleistocene sediments bury deformed older

Neogene sediments (older than 5.6 Ma) in the East Panama deformed belt and the western Gulf of Panama and Pearl Island Basins, and the Panama microplate is now behaving as a rigid indenter with respect to South America. This suggests that internal deformation culminated in the early Pliocene and had effectively ceased by late Pliocene–Pleistocene time.

ACKNOWLEDGMENTS

Much of the Darien region falls within the Comarcas (autonomous regions) of three indigenous peoples, namely, the Kuna (western and northern Darien) and the Embera and Wounaan (central and southern region). This project could not have been completed without the official permission of the congresses of each indigenous group, their hospitality throughout the region, and their help as boatmen and navigators.

The field data for this paper were obtained during a series of Panama Paleontology Project expeditions (Collins and Coates, 1999). Sincere thanks go to Rogelio Cansari and Daniel Castenada, who handled all the logistics and negotiations with the Comarca authorities, and to Helena Fortunato, Antoine Heitz, Jeremy Jackson, Peter Jung, Jorge Obando, and Jay Schneider for assistance in the field. We are especially grateful to Xenia Saavedra, who converted field notes into computerized section logs, prepared graphics, organized the macro- and microfossil samples to ensure that they were entered into the PPP database (<http://www.fiu.edu/~collins/>), distributed samples for processing, and was invaluable in numerous ways at all stages of the manuscript's production. We also thank Helena Fortunato, Magnolia Calderon, Huichan Lin, and Jijun Zhang for preparing samples and specimens, and Susan Schultz and Don McNeill for helping to prepare the geologic map. We are grateful to our GSA Bulletin reviewers, in particular to Peter McCloughlin and Paul Mann, for exceptionally thorough and perceptive criticism that greatly improved the manuscript. This research was supported by National Science Foundation grants DEB-9696123 and DEB-9705289 to LSC, AGC, and Jeremy Jackson (STRI/Scripps Institute, University of California at San Diego) and by grants from the National Geographic Society to AGC and LSC, and the Smithsonian Institution to AGC and Jeremy Jackson.

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MANUSCRIPT RECEIVED BY THE SOCIETY 12 OCTOBER 2002

REVISED MANUSCRIPT RECEIVED 5 DECEMBER 2003

MANUSCRIPT ACCEPTED 15 JANUARY 2004

Printed in the USA

Statement of Ownership, Management, and Circulation (Required by Title 39 U.S.C. 4369)

Bulletin (Publication No. 0016-7606) is published monthly by The Geological Society of America, Inc., (GSA) with headquarters and offices at 3300 Penrose Place, Boulder, Colorado 80301 U.S.A.; and mailing address of Post Office Box 9140, Boulder, Colorado 80301-9140 U.S.A. The Publisher is Jon Olsen; offices and mailing addresses are the same as above. The annual subscription prices are: GSA Members \$80; GSA Associate-Student Members \$40; non-members \$525. The publication is wholly owned by The Geological Society of America, Inc., a not-for-profit, charitable corporation. No known stockholder holds 1 percent or more of the total stock. CEDE & Company, 55 Water Street, New York, NY 10041, holds all outstanding bonds; there are no known mortgagees or holders of other securities. The purpose, function, and nonprofit status of The Geological Society of America, Inc., has not changed during the preceding twelve months. The average number of copies of each issue during the preceding twelve months and the actual number of copies published nearest to the filing date (September 2004 issue) are noted at right.

This information taken from PS Form 3526, signed September 17, 2004 by the Publisher, Jon Olsen, and filed with the United States Postal Service in Boulder, Colorado.

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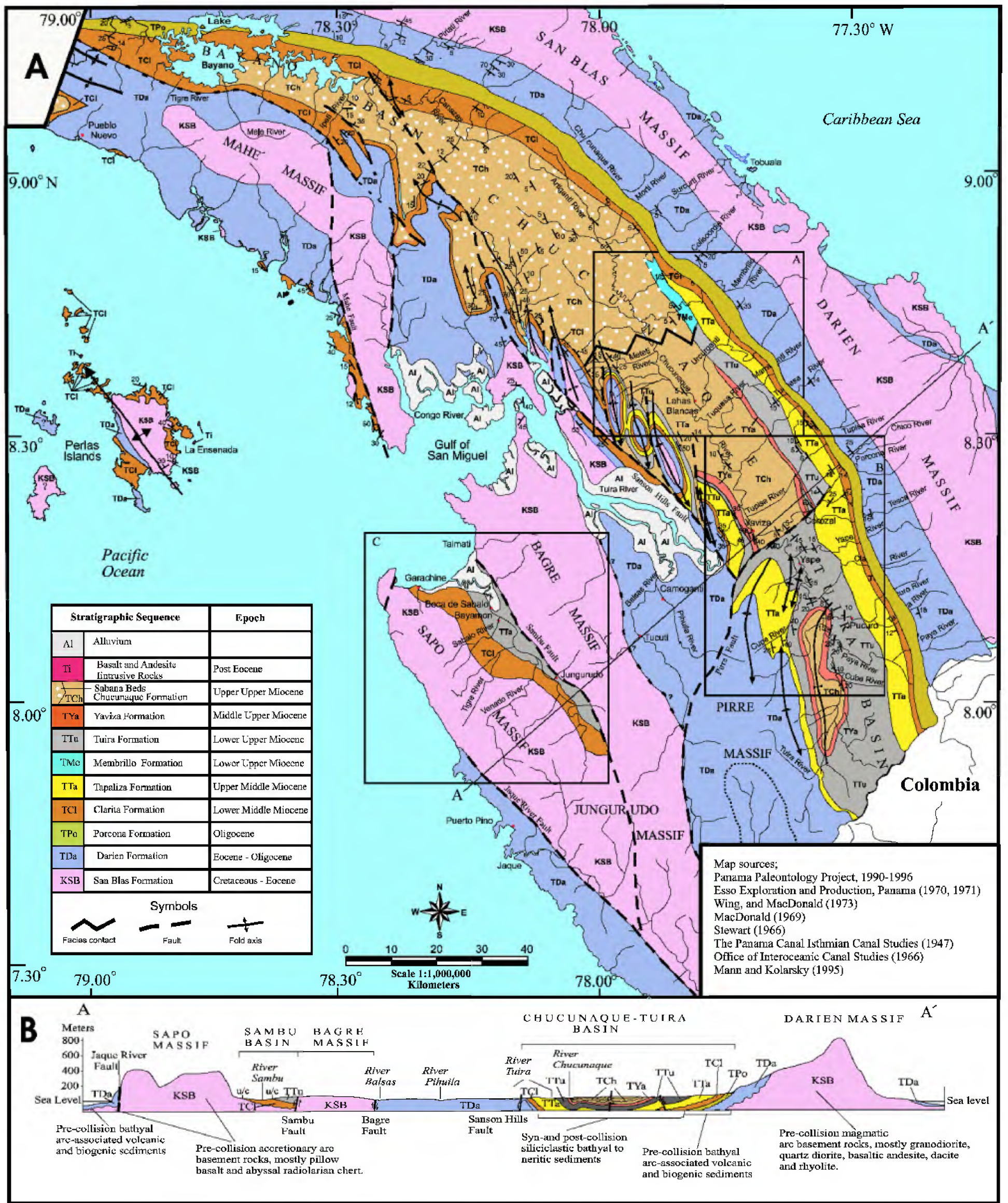


Figure 2. Geologic map (A) and cross section (B) of the Darien region, eastern Panama. Squares A, B, and C locate the PPP sample site locations in Figures DR48-DR50.