Basin Development in an Accretionary, Oceanic-Floored Fore-Arc Setting: Southern Coastal Ecuador During Late Cretaceous–Late Eocene Time

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Abstract

Southern coastal Ecuador is an accreted terrane underlain by an oceanic crust formed during the Aptian-Albian. To the southeast, the oceanic crust is overlain by Cenomanian–Coniacian fine-grained pelagic deposits, coarse-grained volcaniclastic turbidites of Santonian–Campanian age, and Maastrichtian–middle Paleocene tuffaceous shales. Toward the northwest, late Campanian–Paleocene volcaniclastic beds and lava flows of island arc composition rest on the oceanic crust. This results from the opening of a marginal basin between an early Late Cretaceous island arc (Cayo arc) and a latest Cretaceous–Paleocene island arc (San Lorenzo arc).

In the late Paleocene, the accretion of the Cayo remnant arc to the Andean continental margin caused a major deformation phase that affected only the southern part of coastal Ecuador. There, deformation was sealed by thick, coarse-grained, quartz-rich turbidites that constitute the infilling of an early fore-arc or slope basin. A subsequent tectonic event in the early Eocene is believed to have resulted in emergence of the entire area.

At the early–middle Eocene boundary, new fore-arc basins were created that filled with mud and clastic shelf deposits. A marked disconformity is overlain by coastal to continental coarse-grained deposits of late middle–early late Eocene age. These express a major tectonic phase attributed to definitive collision of coastal Ecuador with the Andean margin. The entire area then emerged, until the formation of new fore-arc basins in the latest Oligocene–Miocene.

The late Paleocene, earliest Eocene, and early late Eocene tectonic events are the most important deformation phases to affect southern coastal Ecuador and represent its progressive accretion to the margin. The creation of repeated fore-arc basins can be attributed to subsidence from crustal erosion of the upper plate because each subsidence event succeeded an important compressive phase that must have favored coupling and tectonic erosion. This complex geologic history has implications for burial and maturation of organic matter and must be taken into account in guiding oil exploration in coastal Ecuador.

Resumen

La Costa Sur del Ecuador es un terreno acrecionado formado por una corteza oceánica que se formó en el Aptiano-Albiano. Al Sureste, fué cubierta por depósitos pelágicos finos de edad Cenomaniano-Coniaciano, seguidos por turbiditas volcanoclásticas gruesas del Santoniano-Campaniano y por lutitas tobaceas de edad Maastrichtiano-Paleoceno medio. Al Noroeste, turbiditas volcanoclásticas gruesas y coladas volcánicas de arco insular, datadas del Campaniano-Paleoceno descansan sobre la corteza oceánica. Estos sedimentos se depositaron en una cuenca marginal que se abrió entre un arco insular activo durante la parte temprana del Cretácico superior (arco Cayo) y un arco insular, activo en el Cretácico terminal y Paleoceno (arco San Lorenzo).

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En el Paleoceno superior, una fase de deformación mayor que afectó solo la parte Sur de la costa ecuatoriana representa probablemente la colisión del arco remanente Cayo contra la margen andina. Está sellada por potentes turbiditas gruesas ricas en cuarzo que constituyen el relleno de una primera cuenca de ante-arco o de talud. Un nuevo evento tectónico importante en el Eoceno inferior provocó probablemente la emersión de todo el area.

En el límite Eoceno inferior-medio, una segunda cuenca de antearco se formó y fué rellenada por sedimentos lutáceos y arenosos de plataforma. Una discontinuidad está cubierta por depósitos gruesos costeros o continentales datados del fin del Eoceno medio y base del Eoceno superior. Estos depósitos expresan una fase mayor relacionada con la colisión definitiva de la Costa con la margen andina. La Costa emergió despues, hasta la formación de nuevas cuencas de antearco en el Oligoceno terminal-Mioceno.

Las fases tectónicas del Paleoceno superior, Eoceno inferior y Eoceno superior basal son las más importantes conocidas en la Costa ecuatoriana y traducen su acreción progresiva con la margen. La erosión tectónica parece ser responsable de la creación repetida de cuencas de antearco, ya que cada fase de subsidencia sigue una fase compresiva que, al favorecer la fricción en el plano de subducción, provocaría la erosión mecánica de la base de la placa superior. Dicha evolución sedimentaria discontinua aclara las condiciones de enterramiento y maduración de la materia orgánica, y la estructura geológica compleja que resultó debe ser tenida en cuenta para futuros trabajos de exploración petrolera.

INTRODUCTION

Coastal Ecuador has been identified as an allochthonous terrane of oceanic origin (Goossens and Rose, 1973; Juteau et al., 1977; Lebrat et al., 1987), accreted to the Andean continental margin during Late Cretaceous–early Tertiary time (Feininger and Bristow, 1980; Shepherd and Moberly, 1981; Lebrat et al., 1987). The allochthonous nature of coastal Ecuador is supported by a gravimetric survey (Feininger and Seguin, 1983) and by paleomagnetic studies that show a 70° clockwise rotation of this area has occurred since the middle Cretaceous (Roperch et al., 1987). Since the Eocene, these regions of accreted basement have remained in a fore-arc setting (Figure 1) (Benitez, 1983; Mégard, 1987; Daly, 1989; Marksteiner and Alemán, 1991).

In coastal Ecuador, two main zones have been recognized. They are separated by the present-day Chongón-Colonche fault which has been interpreted as a major paleogeographic feature (Canfield, 1966; Benitez, 1983, 1992). North of the Chongón-Colonche fault, on the Chongón-Colonche Cordillera and in the Manabí basin (Figure 2), the stratigraphic succession is characterized by middle or upper Eocene beds unconformably overlying the Cretaceous–lower Paleocene interval. South of the Chongón-Colonche fault, the stratigraphic succession of the Santa Elena Peninsula is characterized by a thick upper Paleocene sequence and by the development of the deeply subsided Progreso basin of Neogene age (Figure 3).

The occurrence of oil in southern coastal Ecuador motivated several geologic studies that have led to numerous and often contradictory interpretations. In this paper, we present a synthesis of the available stratigraphic and sedimentologic data, as well as new field work and paleontologic studies. These efforts have refined the stratigraphic framework and have enabled us to revise the sedimentologic and paleogeographic interpretations and to modify earlier interpretations of the tectonic and sedimentary evolution of this area. This paper specifically addresses the Cenomanian–Eocene interval, during which the geologic history is marked by changing paleotectonic settings and development of successive sedimentary basins. This study was part of a scientific cooperative agreement between the Ecuadorian state oil company Petroecuador-Petroproducción and the French Institute of Scientific Investigations for Development in Cooperation–ORSTOM.

Figure 1—Location map of the southern coast of Ecuador.

PREVIOUS WORK

The discovery of small oil fields in the southwestern part of the Santa Elena Peninsula at the beginning of this century led to detailed paleontologic and micropaleontologic studies of the Upper Cretaceous and Tertiary stratigraphy of southern coastal Ecuador (e.g., Sinclair and Berkey, 1923; Olsson, 1931, 1942; Thalmann, 1946, Cushman and Stainforth, 1951; Sigal, 1969) and established regional stratigraphic relationships (Sheppard,

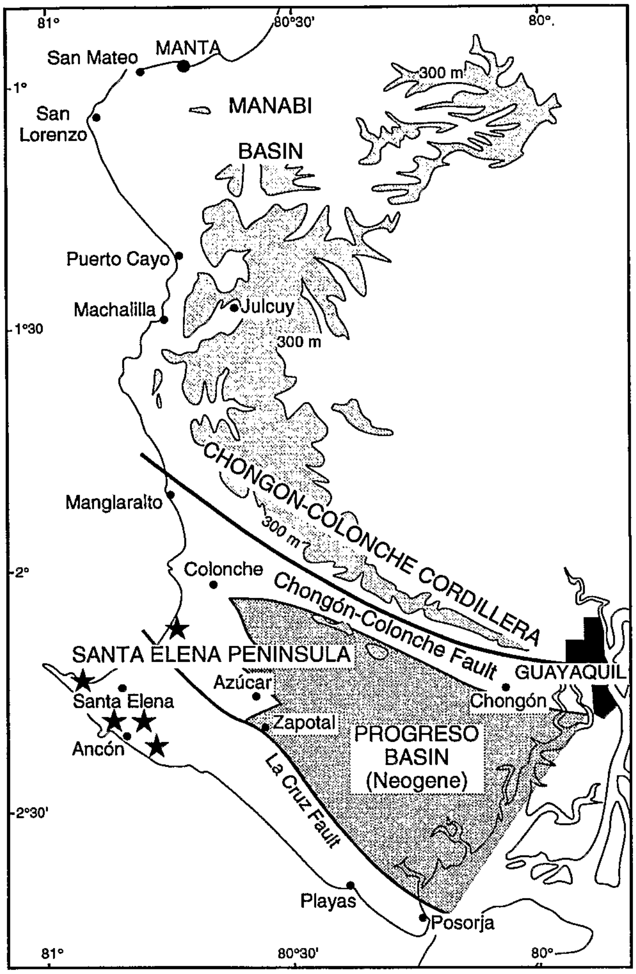

Figure 2—Structural and morphologic setting of southern coastal Ecuador, and location of the main localities cited in the text. Stars indicate oil fields.

1937; Marchant, 1961; Sauer, 1965; Canfield, 1966; Faucher et al., 1971; Faucher and Savoyat, 1973). However, the subsurface studies carried out by different oil companies in specific areas resulted in contradictory local stratigraphic nomenclature and ages.

With emergence of the plate tectonic theory, the apparently confusing stratigraphy, the poor quality and scarcity of outcrops, and the tectonic complexity of the Santa Elena Peninsula area led Azad (Anglo-Ecuadorian proprietary report, 1968) and Colman (1970) to interpret the geology of the Peninsula as a giant olistostrome of late Eocene age and involving Upper Cretaceous–middle Eocene rocks. This interpretation was shared by Bristow and Hoffstetter (1977) and Feininger and Bristow (1980).

In the 1980s, studies carried out by Petroecuador and the Escuela Superior Politécnica del Litoral of Guayaquil (Espol) restored the former stratigraphic framework and elaborated sedimentologic interpretations based mainly on submarine fan models (e.g., Benitez, 1983, 1992; Egüez, 1985; Nuñez del Arco et al., 1986; Santos et al., 1986a; Contreras, 1990). Meanwhile, a large amount of micropaleontologic and geologic work has been carried out by oil companies, most of which is unpublished. In this study, we draw upon both new field observations and an extensive synthesis of biostratigraphic information.

LATE CRETACEOUS–LATE EOCENE TECTONOSTRATIGRAPHIC EVOLUTION

Late Cretaceous–Early Late Paleocene

The basement of coastal Ecuador (Piñon Formation) is made up of massive tholeiitic basaltic and basalt-andesitic lavas generally considered to be a piece of oceanic floor (Goossens and Rose, 1973; Juteau et al., 1977; Feininger and Bristow, 1980; Mégard, 1987; Daly, 1989). However, early chemical studies showed that the Piñon Formation has affinities with island arc volcanic rocks (Goossens et al., 1977; Henderson, 1979). More recently, Lebrat et al. (1987) distinguished the altered and metamorphosed Piñon Formation of N-type MORB composition, dated as late Aptian–Albian (110 ± 10 and 104 ± 15 Ma) (Goossens and Rose, 1973), and the San Lorenzo Formation of island arc nature, which is late Campanian–Paleocene in age and crops out only in the Manabí area (see also Faucher and Savoyat, 1973; Wallrabe-Adams, 1990). The Piñon Formation (Figure 3) crops out in the Guayaquil area, in the Chongón-Colonche Cordillera, and in the southwestern part of the Santa Elena Peninsula and has been recognized in the Manabí basin, thus suggesting that it constitutes the basement of the entire southern coastal Ecuador (Figures 3, 4).

Cenomanian–Coniacian

The Calentura Formation conformably overlies the Piñon Formation (Figure 3) (Alvarado and Santos, 1983; Benitez, 1990). It is a 200-m-thick succession of shales, black laminated limestones, and thin-bedded graywacke turbidites that were deposited in a pelagic, partially anaerobic environment and that include a few thin-bedded volcanic breccias and hyaloclastites. The foraminifera indicate a late Cenomanian–Turonian age (Thalmann, 1946; Sigal, 1969), which has been partially confirmed by the discovery of a Turonian ammonite (R. Marocco, 1992, personnal communication). Nannofossils indicate an early Coniacian age (Gamber et al., 1990). The Calentura Formation is known in the Guayaquil area and the eastern part of the Chongón-Colonche Cordillera, but has not been recognized farther west. The Calentura Formation is attributed to starved, deep-marine pelagic sedimentation deposited in Cenomanian–early Coniacian time on the young Piñon oceanic crust (Figure 4).

Santonian–Campanian

Guayaquil Area The Cayo Formation conformably overlies the Calentura Formation (Benitez, 1990; Marksteiner and Alemán, 1991). It crops out on both sides of the Chongón-Colonche fault. The Cayo Formation is a

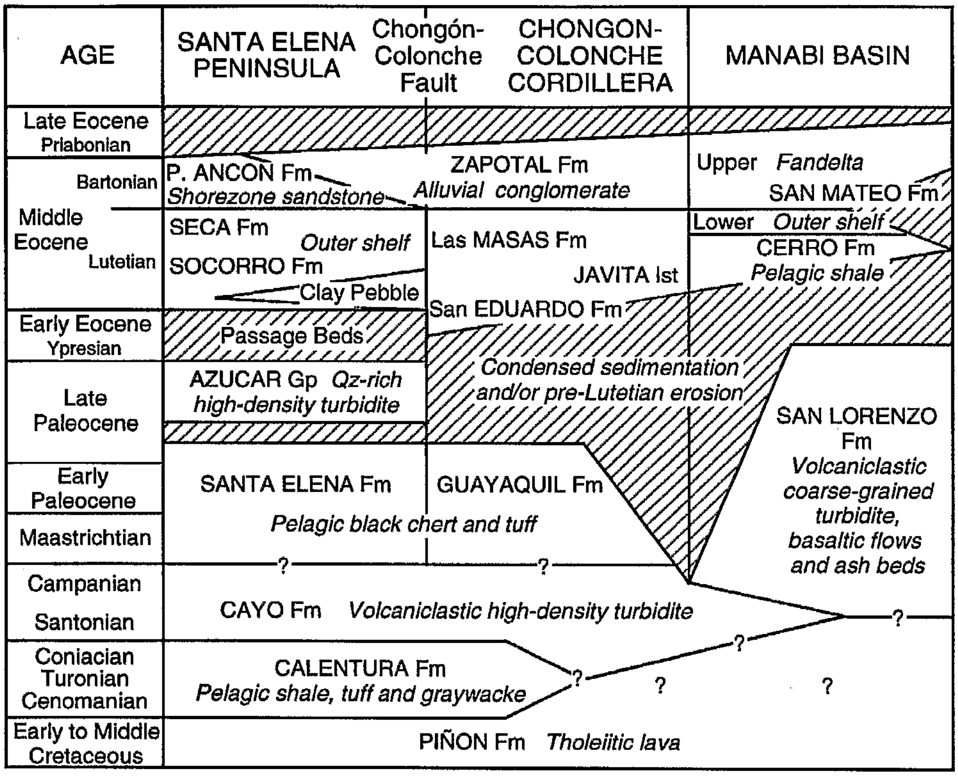

Figure 3—Stratigraphic framework of the sedimentary units of southern coastal Ecuador.

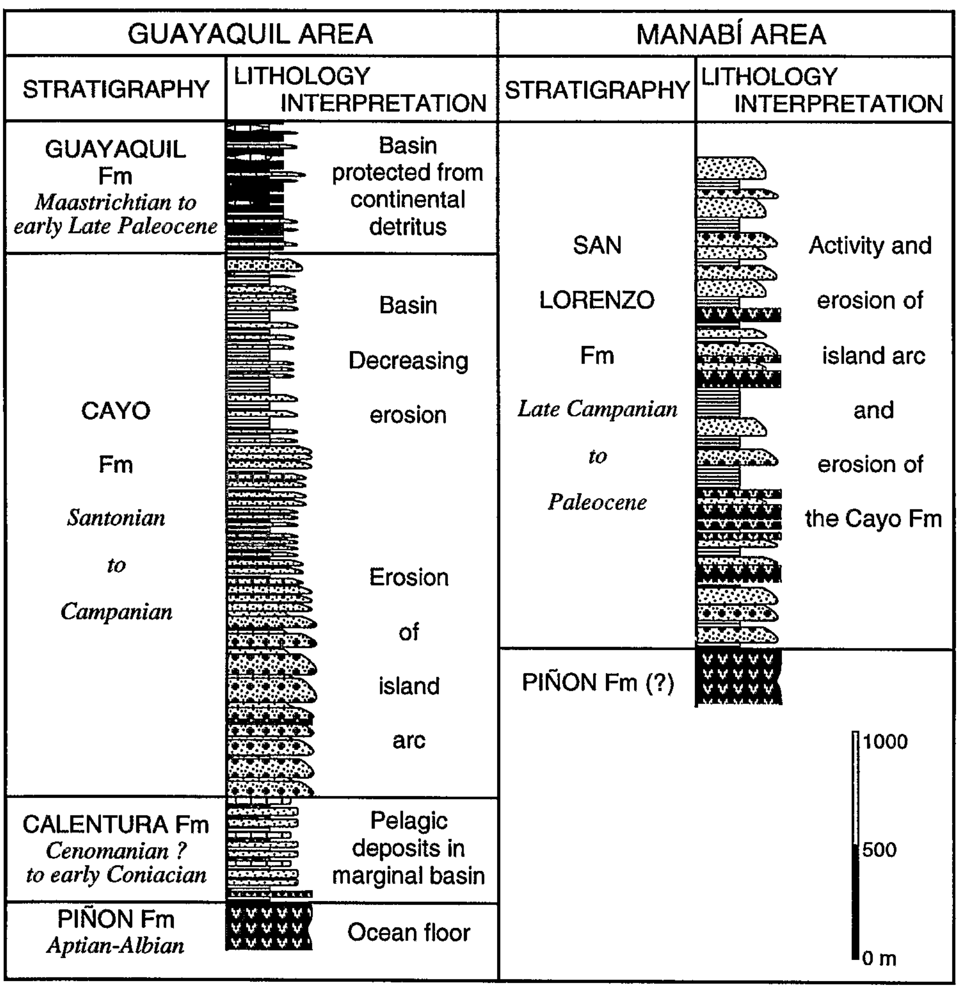

Figure 4—Stratigraphy and environment of the Cretaceous–middle Paleocene deposits of southern coastal Ecuador in the Guayaquil area (after Benitez, 1990; Marksteiner and Alemán, 1991) and the Manabí area (after Faucher et al., 1971).

2000-m-thick succession of fining-upward, coarse-grained volcaniclastic sandstones and conglomerates, including a spectrum from high- to low-density turbidites with shaly intercalations (Figure 4). Planktonic foraminifera and dinocysts indicate a late Santonian–Maastrichtian age (Thalmann, 1946; Bristow 1976; Benitez, 1990; Gamber et al., 1990). Reworked foraminifera indicate a shallow-marine provenance, and scarce paleocurrent data suggest a west-directed transport (Benitez, 1990). This coarse-grained sedimentation contrasts markedly with the underlying fine-grained deposits and indicates that an important tectonic and geodynamic change occurred by late Coniacian–early Santonian time. The Cayo Formation is attributed to erosion of a volcanic terrain, which is thought to have been an island arc (Wallrabe-Adams, 1990; Marksteiner and Alemán, 1991) (Figure 4). However, further geochemical and mineralogic studies are necessary to identify the provenance precisely.

Manabí Area Coarse-grained volcaniclastic conglomerates associated with basalt flows and dikes that were known as the Cayo Formation (Faucher et al., 1971) are now referred to as the San Lorenzo Formation (Lebrat et al., 1987) (Figure 4). These beds rest on massive basalts ascribed to the Piñon Formation (Faucher et al., 1971). They have yielded late Campanian radiolarians at Machalilla (Romero, 1990). In the Manta area, interbedded pillowed basalts as well as dikes and small plutons cross cutting the formation have yielded Santonian–early Eocene radiometric ages (85–52.9 Ma), with a maximum during the late Campanian–early Maastrichtian (77–72 Ma) (Goossens and Rose, 1973; Hall and Calle, 1982; Pichler and Aly, 1983; Lebrat et al., 1987; Wallrabe-Adams, 1990). These volcanic rocks have an island arc composition and are much less altered than the rocks of the Piñon Formation (Lebrat et al., 1987). At Machalilla, the occurrence of numerous andesitic boulders and clasts derived from the Cayo Formation indicates that the deposition is coeval with synsedimentary tectonic deformation that caused subaerial erosion of the formation. Paleocurrents are locally directed toward the WSW (Romero, 1990). Chemical and geologic data have shown that the San Lorenzo Formation can be attributed to erosion of an active island arc (Lebrat et al., 1987; Marksteiner and Alemán, 1991).

Maastrichtian–Early Late Paleocene

South of Chongón-Colonche Fault The Santa Elena Formation crops out only in the Santa Elena Peninsula (Figures 3, 5). It has long been considered a stratigraphic equivalent of the Guayaquil Formation (Sinclair and Berkey, 1923; Thalmann, 1946; Canfield, 1966). We have recently confirmed this interpretation. Some outcrops on the peninsula have yielded the radiolarians *Amphypyndax tylotus*, *Archaeodictyomitra lamellicostata*, *Diacanthocapsa granti*, and *Stylospongia* sp., among others, and the calcareous nannofossils *Arkhangelskiella* cf. *scapha*, *Coccolithus paenepelagicus*, *Micula decussata*, *Quadrum gartneri*, and *Watznaueria barnesae*, which indicate a latest Cretaceous age. In other samples, the radiolarians *Bathropyramis* sp., *Buryella* aff. *tetradica*, *Cenosphaera* sp., *Dictyomitra* aff. *andersoni*, *Lychnocanoma* sp., *Phormocyrtis striata exquisita*, *Protoxiphotractus* sp., and *Stylosphaera* sp. indicate a Paleocene age. These outcrops are altered, weakly metamorphosed (Sheppard, 1937), and intensely deformed, thus precluding any precise estimate of thickness or detailed sedimentologic analysis (Figure 5). However, the lithology is comparable to that of the Guayaquil Formation, suggesting a similar depositional environment.

The deformation of the Santa Elena Formation involves gently southward-dipping shear planes and tight folds with ENE-WSW to WNW-ESE trending axes, associated with a penetrative axial plane cleavage dipping gently toward the south. The overall deformation of the formation clearly increases toward the southwest. The orientations of axial cleavages and shear planes, the warping of the folds, and the analysis of the displacement criteria indicate a heterogeneous deformation associated with north- to NNW-directed thrust vergence. Because it affects lower upper Paleocene beds (Santa Elena Formation) and is covered by uppermost Paleocene coarse-grained deposits, this major tectonic event is of late Paleocene age (about 57 ± 2 Ma, according to Haq et al., 1987).

Northeast of Chongón-Colonche Fault The little deformed Guayaquil Formation conformably and gradationally overlies the Cayo Formation (Figures 4, 5). It crops out only north of the Chongón-Colonche fault. It consists of about 400 m of dark, siliceous tuffs and shales, with numerous cherts and subordinate thinly bedded turbidites, which contrast with the underlying coarse-grained Cayo Formation. Thalmann (1946), Sigal (1969), and Faucher et al. (1971) identified planktonic foraminifera of Maastrichtian age, with a probable extension into the Paleocene. This was confirmed by Benitez (1991), Gamber et al. (1990), and our work because of nannofossils and radiolarians that indicate an early late Paleocene age (tympaniformis zone) for the top of the formation near the town of Guayaquil.

The Guayaquil Formation is attributed to pelagic sedimentation that was coeval with mild or distal volcanic activity (Figure 4). The lack of any significant quartz-rich detritus suggests either that southern coastal Ecuador was located far from a continental source or that the area was sheltered from any significant continental detrital supply. The increasing amount of calcareous nodules or beds toward the top of the unit suggests a slight shallowing-upward trend (Benitez, 1991) and possibly a deepening of the carbonate compensation depth (CCD). The late Paleocene tectonic phase that followed the deposition of the Santa Elena Formation ended this phase of sedimentation.

Northwest of the Chongón-Colonche Fault In the Manabí area, coarse-grained graywackes intercalated with basaltic flows and ash beds yield Maastrichtian–Paleocene(?) microfaunas (Sigal, 1969; Faucher et al., 1971), which are consistent with the Maastrichtian–Paleocene radiometric ages obtained from the top of the

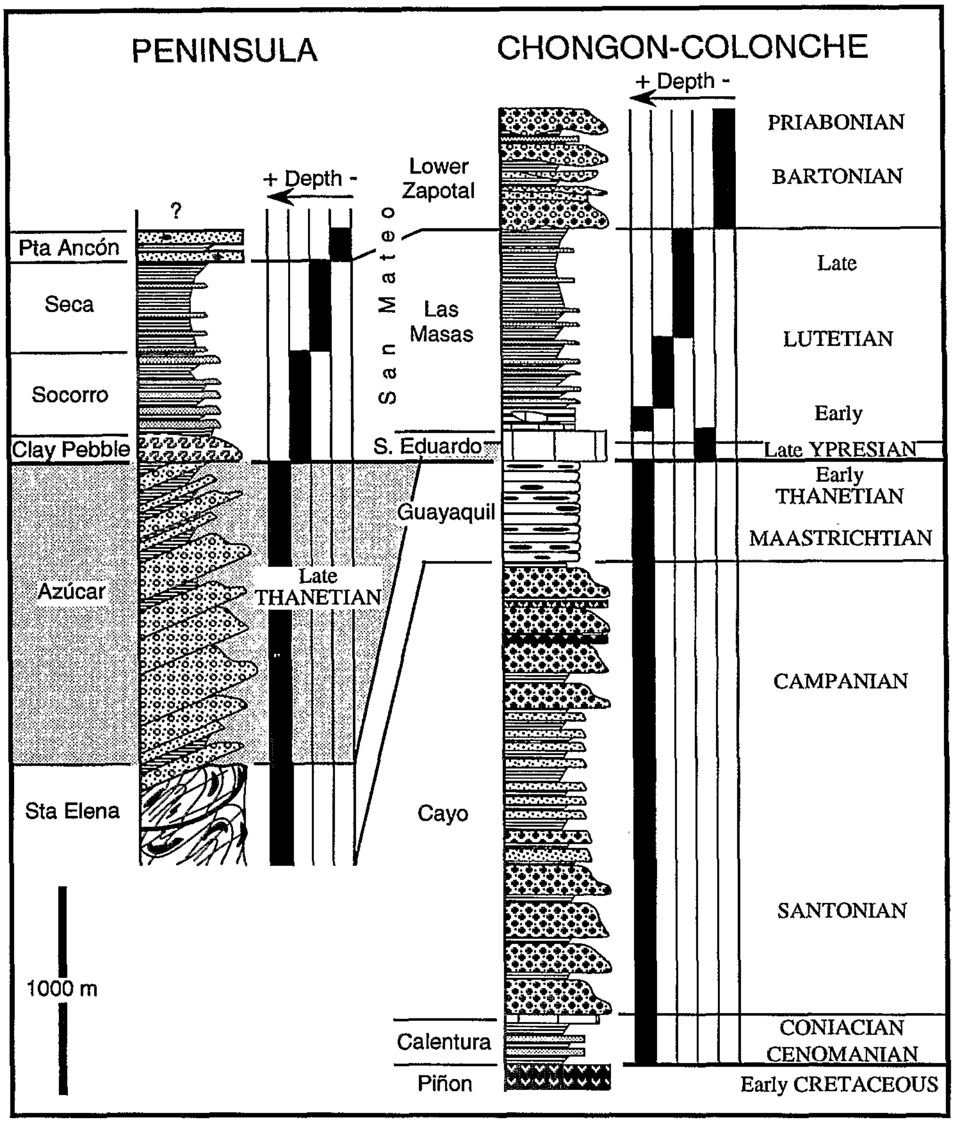

Figure 5—The Upper Cretaceous–upper Eocene stratigraphy of the Santa Elena Peninsula and Chongón-Colonche Cordillera.

San Lorenzo Formation (Hall and Calle, 1982; Lebrat et al., 1987; Wallrabe-Adams, 1990). Therefore, magmatic activity related to an island arc went on in this area while the Guayaquil and Santa Elena formations were being deposited (Figure 4). This observation, together with the lack of Cenomanian–Coniacian deposits in this area, suggests that the volcaniclastic sedimentation is diachronous and the volcanic activity migrated from the Guayaquil area in the early Late Cretaceous and toward the Manabí area in the latest Cretaceous–Paleocene.

Late Paleocene–Early Eocene

Late Paleocene

The conspicuous Azúcar Group is known only south of the Chongón-Colonche fault (Figures 3, 5). Although the lower contact has not been observed, it is most probably unconformable on the Santa Elena Formation, as suggested by the analysis of seismic lines (Marksteiner and Alemán, 1991). The Azúcar Group consists of at least 1500 m of conglomerates, pebbly sandstones, sandstones, and shales (Bristow and Hoffstetter, 1977). These sediments were deposited on submarine fans largely by high-density turbidites, with a minor amount of low-density flows (Moreno, 1983; Benitez, 1983). Various formations have been recognized (Marchant, 1961; Small, 1962; Canfield, 1966). However, their stratigraphic succession is not established and they cannot be used for mapping purposes, thus detracting from their usefulness (Benitez, 1992).

On the basis of benthonic foraminifera, the Azúcar Group has long been considered early Paleocene in age (Thalmann, 1946; Small, 1962; Benitez, 1992; Marksteiner and Alemán, 1991), although the mollusk fauna suggests a younger age (Olsson, 1942; Canfield, 1966; Sigal, 1969; Faucher et al., 1971; Daly, 1989). In contrast, the planktonic foraminifera (e.g., *Globigerina* cf. *velascoensis*, *G. triloculinoides*, *G.* aff. *daubjergensis*, *Globorotalia angulata* and *G. mackannai*, Small, 1962; Moreno, 1983; Litton Resources proprietary report, 1986; Gamber et al., 1990) are of middle–late Thanetian age (pseudomenardii and velascoensis zones), and indicate that most of the benthonic foraminifera are reworked (Figure 5).

In the southern part of the Santa Elena Peninsula, conglomeratic clasts are mainly derived from the Santa Elena and Guayaquil formations, continental basement, and volcanic rocks (Marksteiner and Alemán, 1991). This indicates that the Cretaceous strata were deformed and subjected to substantial erosion and that the Santa Elena Peninsula was in contact with the Andean continental margin. Paleocurrents indicate a north-northeastward transport direction (Moreno, 1983) (Figure 6). In contrast, in the northern Santa Elena Peninsula, the amount of volcanic clasts is much greater (Marksteiner and Alemán, 1991) and preliminary results suggest southwest-directed paleocurrents. The drastic change of provenance with respect to older deposits is clearly related to the major phase of late Paleocene deformation, and the Azúcar Group postdates this event.

The Azúcar Group is also well structured, including faulting and ENE-WSW-trending tight folds with vertical axial planes. This tectonic phase is assigned to the early Eocene because similar deformation is not present in the overlying Lutetian sequence. As a consequence, the observed deformation of the Santa Elena Formation apparently resulted from superimposition of an early phase characterized by ESE-WNW-trending, warped tight folds of late Paleocene age, which affected only the Santa Elena Formation, with a later ENE-WSW-trending deformation which affected the Santa Elena Formation as well as the Azúcar Group.

The Early Eocene Problem

The early Eocene was marked by a widespread sedimentary hiatus. Although no formations of this age are known in southern Ecuador, some studies report early Eocene fossils from poorly known beds (Figure 3 and 5).

South of Chongón-Colonche Fault In the Santa Elena Peninsula, the "Passage beds" and equivalent units were only recognized in well cutting samples; there are no direct data of a sedimentologic nature. These beds, the thickness of which varies up to 350 m, have a lenticular shape and consist of two distinct horizons. The first comprises shales and micaceous sandstones bearing planktonic foraminifera of early Eocene age (*Globigerina* aff. *stonei*, *Globorotalia* aff. *acuta*, *G.* aff. *aequa*, *G. crassata*) which are associated with reworked benthonic foraminifera (Thalmann, 1946; Small, 1962; Bristow and Hoffstetter, 1977). The second layer includes locally conglomeratic sandstones and shales with plant remains and is characterized by species of *Discocyclina* (Barker, 1932; Anglo-Ecuadorian Oilfields proprietary report, 1956), suggesting a correlation with the lowest Lutetian beds of northwestern Peru which contain a similar foraminiferal fauna (González, 1976).

The "lower Passage beds," containing mainly planktonic foraminifera, may represent the end of the preserved remnants of the uppermost Paleocene marine sedimentary cycle (Azúcar Group). In the "upper Passage beds," which are apparently absent north of the Chongón-Colonche fault, the presence of plant fragments and benthonic foraminifera indicates a shallow marine environment. The upper Passage beds may therefore

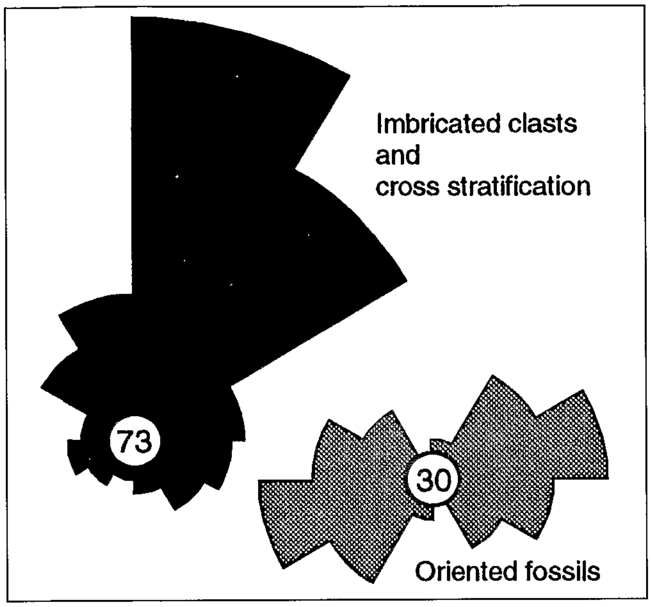

Figure 6—Paleocurrents measured in the Azúcar Group (latest Paleocene) in the Playas area (Santa Elena Peninsula). (After Moreno, 1983.)

represent the lenticular "basal conglomerate" of the overlying mainly Lutetian sedimentary cycle.

North of Chongón-Colonche Fault West of Guayaquil on the southern side of the Chongón-Colonche Cordillera, planktonic foraminifera and calcareous nannofossils of latest Paleocene–early Eocene age have been recognized in limestone samples (Unocal proprietary report, 1987), which probably correspond to the base of the San Eduardo Formation. In both areas, the lower Eocene sedimentation is either condensed or thinned by erosion. These characteristics suggest that the early Eocene hiatus resulted from widespread, possibly diachronous emergence that occurred between earliest Ypresian and earliest Lutetian times.

Late Early Eocene–Early Middle Eocene (Late Ypresian–Lutetian)

Late Ypresian–early Lutetian time was characterized by a widespread transgression associated with tectonic subsidence, which allowed deposition of a thick, shallowing-upward marine sequence. North of the Chongón-Colonche fault, the transgression is markedly diachronous; it overlies deeply eroded rocks and is associated with conspicuous synsedimentary tectonism. This diachronism, together with the variable facies, has resulted in numerous poorly defined stratigraphic units.

Late Early Eocene–Middle Lutetian Transgression

South of Chongón-Colonche Fault In the Ancón area, the Clay Pebble beds overlie the upper Passage beds. The Clay Pebble beds consist of up to 700 m of disrupted

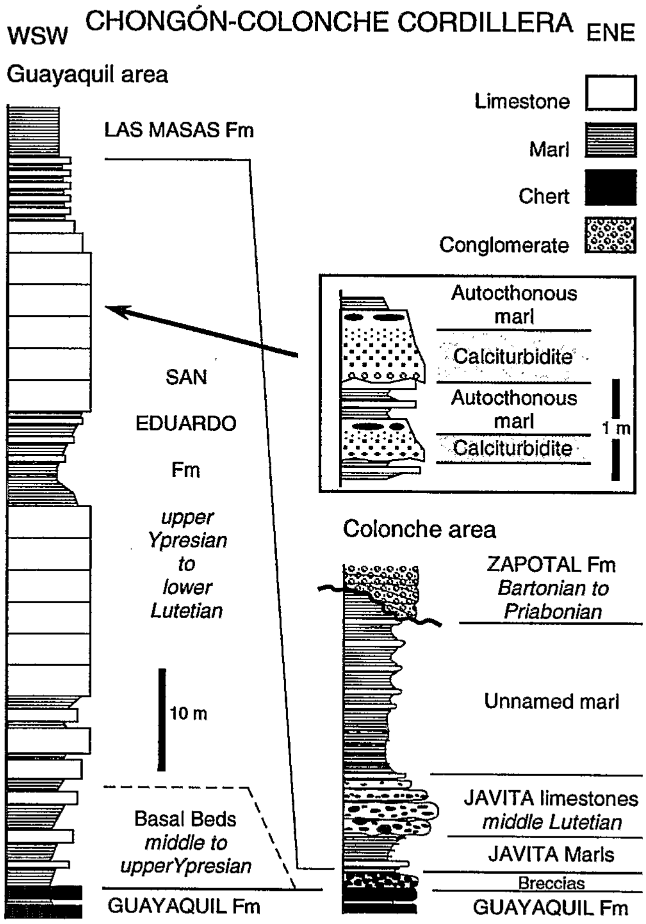

Figure 7—Stratigraphic correlations of the Lutetian transgressive deposits in the Chongón-Colonche Cordillera.

shales, including clasts and contorted beds of pebbly sandstones, sandstones, shales, cherts, and limestones (Figure 5). They represent large-scale slumps (Brown and Baldry, 1925; Marchant and Black, 1960; Marksteiner and Alemán, 1991) that express instability of the substratum. The Clay Pebble beds do not constitute a formation, but rather a diachronous facies that occurs at the base and within the lower part of the Lutetian sequence (Anglo-Ecuadorian Oilfields proprietary report, 1956). In the Ancón oil field, its age ranges from latest Ypresian to early Lutetian (Bristow and Hoffstetter, 1977; Jiménez and Mostajo, 1990). In other regions of the peninsula, the Lutetian beds unconformably overlie Cretaceous or lower Tertiary rocks and contain at the base a 0- to 30-m-thick, coarse-grained basal conglomerate of early–middle Lutetian age (Small, 1962; Bristow and Hoffstetter, 1977; Rosario conglomerate of Benitez, 1992).

North of Chongón-Colonche Fault North of the Chongón-Colonche fault, the early Lutetian transgression is generally expressed by the San Eduardo Formation which consists of 30–120 m of well-stratified calciturbidites deposited within autochthonous, hemipelagic marls and micrites (Santos et al., 1986b) (Figures 5, 7). West of Guayaquil, the base of the formation consists of a few meters of bedded cherty marls and shales (Figure 8). We have identified radiolarians (*Lamptonium* cf. *fabaeforme, Orbula discipulus, Phormocyrtis striata exquisita*), calcareous nannofossils (*Fasciculithus tympaniformis, Heliolithus kleinpelli, H.* cf. *riedelli, Tribrachiathus orthostylus*), and planktonic foraminifera (*Globigerina* aff. *primitiva, G.* aff. *collactea, Globorotalia aequa, G. broedermanni, G. esnaensis, G. pseudotopilensis, G. wilcoxensis*), which range from late Paleocene to late early Eocene in age. These are associated with reworked Cretaceous benthonic foraminifera. We interpret the base of the San Eduardo Formation as middle–late Ypresian in age (aragonensis zone). The overlying calciturbidites contain numerous algae, oncolites, and benthonic foraminifera (*Discocyclina* and *Asterocyclina*). Together with associated calcareous nannofossils and planktonic foraminifera, they indicate an earliest Lutetian age (Bristow and Hoffstetter, 1977; Gamber et al., 1990). At the top of the formation, we found radiolarians (*Podocyrtis* aff. *diamesa, Thyrsocyrtis hirsuta*) of late Ypresian–early Lutetian age (P 9–10 zones). In the western part of the Manabí basin, the San Eduardo Formation unconformably overlies Upper Cretaceous rocks, whereas in the eastern part of the Chongón-Colonche Cordillera, it conformably overlies the Paleocene Guayaquil cherts, thus suggesting a westward increase of pre-Lutetian erosion (Figure 8).

In the western part of the Chongón-Colonche Cordillera northeast of Colonche (Figure 2), the brecciated Guayaquil Formation is overlain by thin lower Lutetian marls. These in turn are overlain by a few meters of fining-upward calcareous conglomerates that reworked oncolitic limestones, and some Maastrichtian–Paleocene cherts (Javita limestones) (Sigal, 1969; Benitez, 1992) (Figures 7, 8).

In most of the Manabí basin, the Lutetian transgression is reflected in radiolarian-bearing, fine-grained shales, tuffaceous cherts, and siliceous limestones of pelagic origin that are dated as middle Lutetian (Cerro Formation, base of the San Mateo and Punta Blanca formations) (Sigal, 1969; Bristow and Hoffstetter, 1977; Romero, 1990). These beds either conformably overlie the San Eduardo Formation or unconformably rest on the Senonian San Lorenzo Formation (Figure 8). They commonly contain breccias, reworked Cretaceous microfauna, and olistoliths of Cretaceous rocks (Schulman et al., 1965), which indicate that the early–middle Lutetian transgression was associated with tectonism and erosion.

Lutetian Sequence

After the diachronous and tectonically driven transgression of late Ypresian–middle Lutetian age, the rest of the Lutetian corresponds to a shallowing-upward sequence of marine shelf deposits (Figure 5).

South of Chongón-Colonche Fault In the Santa Elena Peninsula, the Lutetian sequence is 1000–1500 m thick and comprises the Clay Pebble beds and the Socorro and Seca formations (Anglo-Ecuadorian Oilfields proprietary

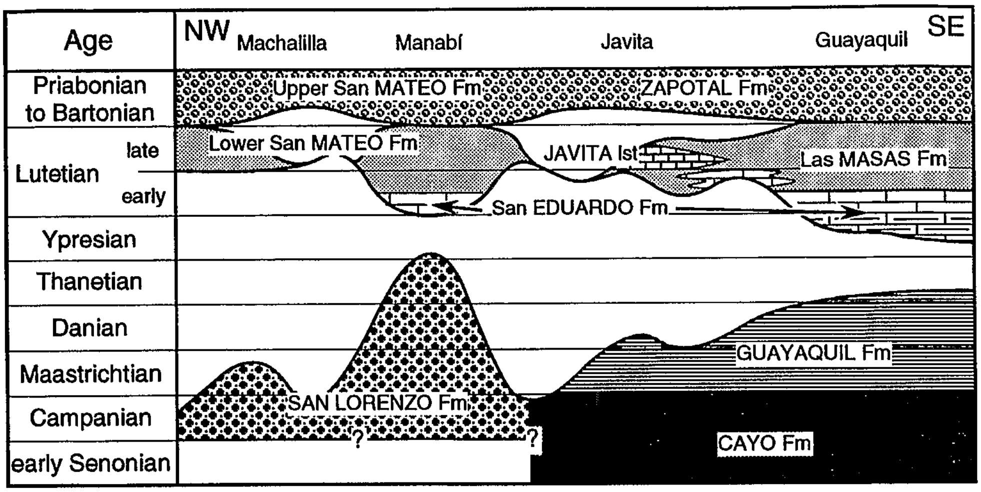

Figure 8—Chronostratigraphic sketch of the middle Ypresian–Lutetian transgression along the Chongón-Colonche Cordillera.

report, 1956) (Figure 5). The Socorro Formation consists of laminated shales, siltstones, and fine-grained sandstones of an outer shelf environment, intercalated with some thick-bedded turbiditic sandstones. Slumped beds (including Clay Pebble facies) and turbidites are common near the base and decrease upward, suggesting a decrease in tectonic activity. The Socorro Formation grades upward into the Seca Formation, a sequence of laminated shales, siltstones, and marls that reflect climatic or seasonal influences, as well as thin-bedded sandstones attributed to storm processes and subordinate turbidites (Figure 9). In the Seca Formation, the upward increase of bioturbation, calcareous content, and neritic fauna indicate a shallow shelf environment. The Socorro and Seca formations contain calcareous nannofossils, planktonic foraminifera, radiolarians, mollusks, and reworked benthonic foraminifera in the turbiditic beds, which together indicate an early–late Lutetian age (Bristow and Hoffstetter, 1977; Jiménez and Mostajo, 1990; Gamber et al., 1990). Sedimentary measurements indicate NNW- to WNW-directed paleocurrents and a northwest-dipping paleoslope (Figure 9).

North of Chongón-Colonche Fault In the southern part of the Chongón-Colonche Cordillera, the 350-m-thick Lutetian sequence is known as the Las Masas Formation. In the Manabí basin, contemporaneous beds are 500–1500 m thick and correspond to the lower part of the San Mateo Formation (Figures 5, 8). The foraminiferal and radiolarian content indicate a Lutetian–early late Eocene age for the entire San Mateo Formation (Cushman and Stainforth, 1951; Sigal, 1969; Bristow and Hoffstetter, 1977; Navarrete, 1986; Contreras, 1990). However, the Bartonian and late Eocene faunas were probably found in the coarse-grained upper part of the formation. The Las Masas and lower San Mateo formations are made up of partially calcareous shales, siltstones, sandstones, and graywackes. South of Puerto Cayo, thin-bedded turbidites, tempestites, and rippled beds indicate a shelf environment that was shallower than that of the Cerro Formation. In San Mateo west of Manta, the 700-m-thick Lutetian–Bartonian San Mateo Formation (Contreras, 1990) includes plant fragments, secondary gypsum veinlets, and heavy mineral laminae and exhibits characteristics typical of clastic shore zone sequences (shoreface to foreshore). Although no complete section has been studied, the depositional environment and evolution are thought to be comparable to that of the Socorro and Seca formations of the Santa Elena Peninsula. In the Manabí basin, undated layers of the San Mateo Formation locally rest on volcanic rocks ascribed to the Lower Cretaceous Piñon Formation (Figure 8).

Middle–Late Eocene (Bartonian–Early Priabonian)

In southern coastal Ecuador, the middle Eocene sequence ends with continental to shallow marine coarse-grained graywackes and lithic sandstones that abruptly overlie the Lutetian marine sequence. These deposits are called the Punta Ancón Formation along the present-day coast of the Santa Elena Peninsula and the San Mateo Formation (upper part) in the Manabí basin (Figures 5, 8). On the inner part of the Santa Elena Peninsula and in the Chongón-Colonche Cordillera, the so-called Zapotal Formation apparently comprises two stratigraphic units. One consists of coarse-grained, poorly dated, continental to coastal deposits with molluscan fauna (Hannatoma fauna) and rare marine microfauna that broadly correlate with the lower Priabonian beds of northern Peru (Verdún Formation) (Olsson, 1931; Paredes, 1958; González, 1976; Bristow and Hoffstetter, 1977). The other unit consists of fine-grained, clastic marine deposits dated as late Oligocene–early Miocene by planktonic foraminifera, suggesting that it belongs to the overlying mainly Neogene sedimentary cycle (Bristow, 1975; Bristow and Hoffstetter, 1977). We agree with Olsson (1931), Canfield (1966), and Sigal (1969) that the coarse-grained lower part of the Zapotal Formation is partially equivalent to the Punta Ancón Formation of Bartonian–early Priabonian age. This implies that a major sedimentary hiatus of Oligocene age separates the lower and upper parts of the Zapotal Formation.

We are able to confirm the Bartonian age of the Punta

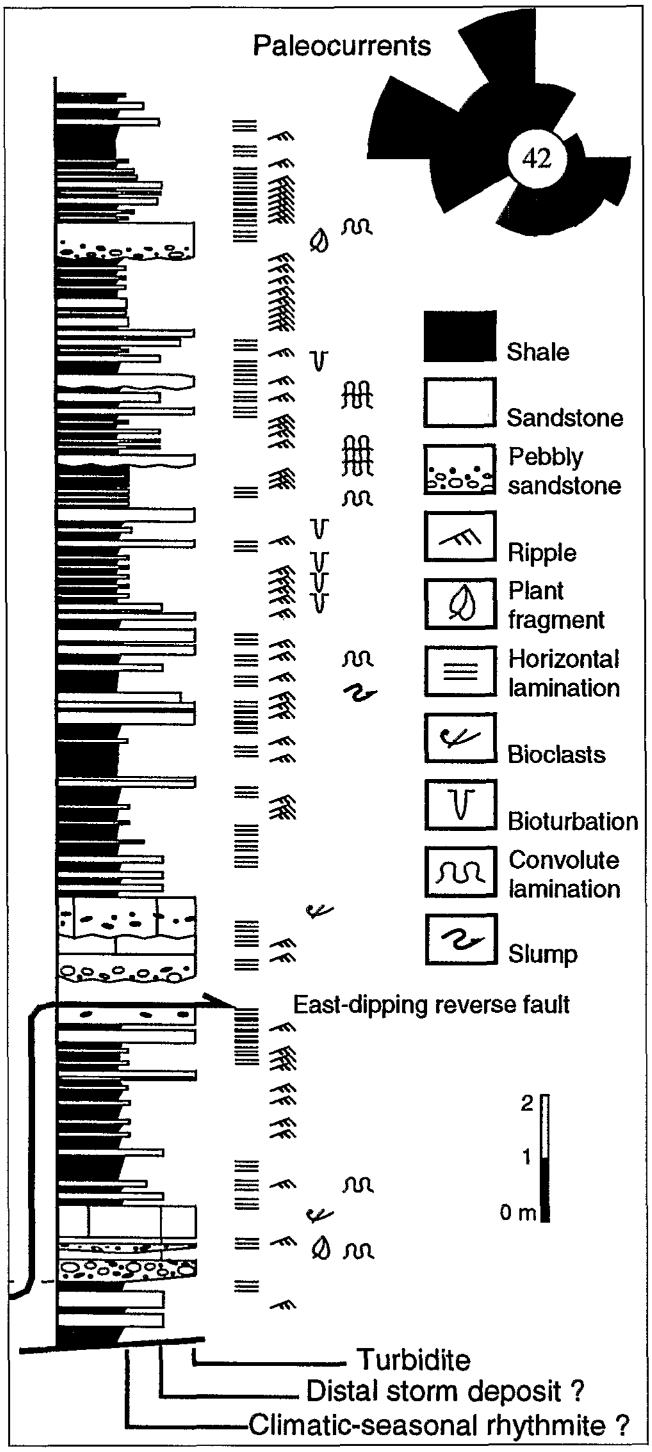

Figure 9—Stratigraphic section and paleocurrent data for the Socorro and Seca formations (Lutetian) in the Punta Ancón beach area (Santa Elena Peninsula).

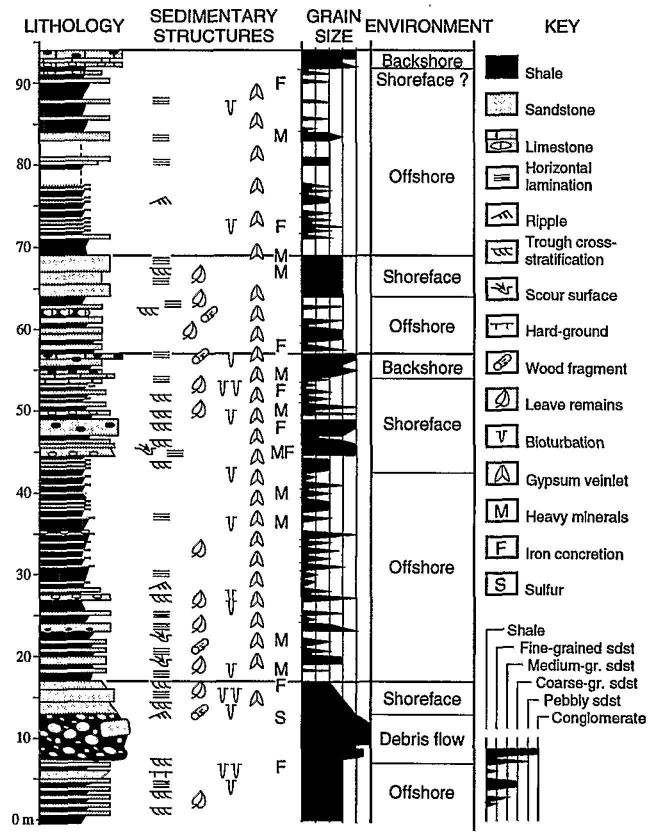

Figure 10—Stratigraphic section of the Punta Ancón Formation (Bartonian) in the Punta Ancón beach area (Santa Elena Peninsula).

Ancón Formation (Bristow and Hoffstetter, 1977; Jiménez and Mostajo, 1990) on the basis of rich radiolarian associations. In the southwestern part of the Santa Elena Peninsula, the formation consists of reddish shales and siltstones, lithic sandstones, and subordinate conglomerates, all of which are organized in typically thickening- and coarsening-upward clastic sequences of shore zone origin (Figure 10). Locally, massive conglomeratic facies (west of Ancón, east of Playas) are interpreted as large fluvial or distributary channels that fed into the clastic coastal system. Measurements indicate southwest- to northwest-directed paleocurrents perpendicular to the present-day coast (see Figure 12). The amount of conglomerates markedly increases northward, and in the Colonche area, the Punta Ancón Formation grades eastward into the lower Zapotal Formation.

The lower Zapotal Formation is a 300–600 m thick succession of lithic sandstones and coarse-grained conglomerates deposited in an alluvial environment. An intermediate layer contains plant-bearing shales and subordinate sandstones (Small, 1962; Canfield, 1966). These argillaceous beds are believed to correlate with the upper Eocene Jusa Formation which is exposed 15 km ESE of Colonche (Cushman and Stainforth, 1951; Bristow and Hoffstetter, 1977). In the Chongón-Colonche Cordillera, the lower Zapotal Formation overlies either Upper Cretaceous–Paleocene or middle Eocene deposits and consists of coarser grained alluvial fan deposits. These grade southward into finer grained deposits of alluvial plain or coastal environment in the Santa Elena Peninsula. At the southeastern end of the Peninsula (Posorja, Figure 2), the lower Zapotal Formation consists of coastal sandstones similar to those of the Punta Ancón

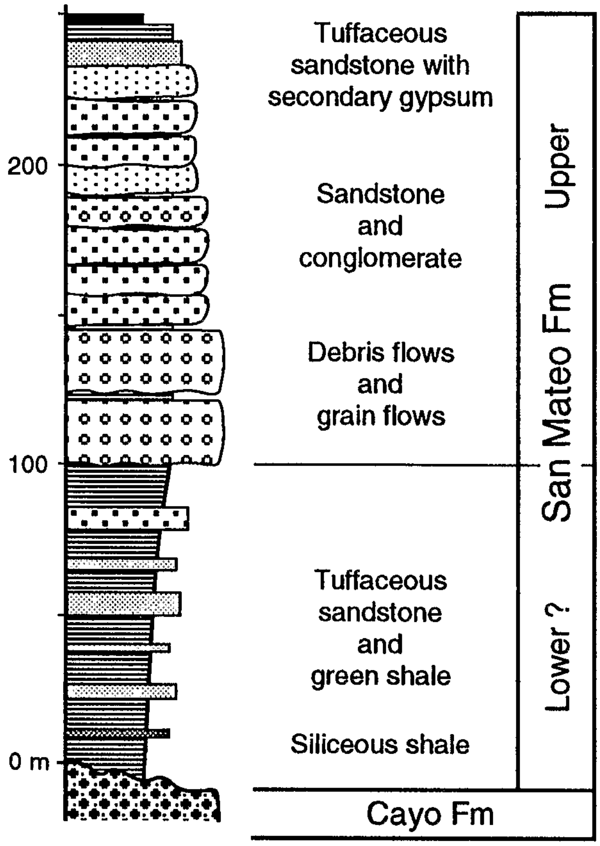

Figure 11—Stratigraphic column of the San Mateo Formation (middle–upper Eocene) in the Julcuy area. (Simplified after Egüez, 1985.)

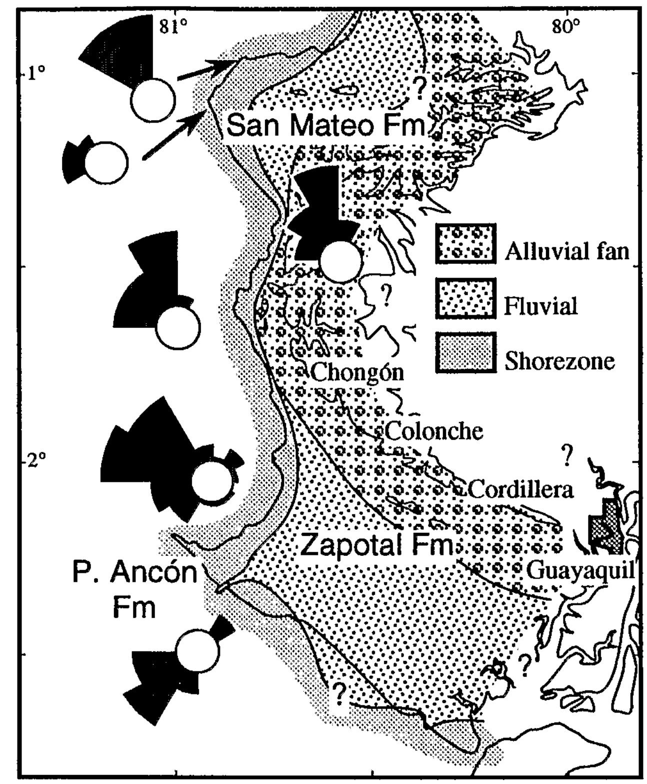

Figure 12—Paleocurrents and paleogeographic interpretation of the Bartonian–early Priabonian deposits of southern coastal Ecuador.

Formation and contains the Hannatoma molluscan fauna of early late Eocene age (Olsson, 1931; González, 1976).

North of Manglaralto, the Punta Ancón Formation grades northward into conglomerate-prone deposits that correspond to the upper part of San Mateo Formation of Bartonian–early Priabonian age (Cushman and Stainforth, 1951; Sigal, 1969; Navarrete, 1986; Contreras, 1990). Along the present-day coast, it consists of a few hundred meters of coarse-grained conglomeratic lenses and beds of alluvial origin intercalated within the shoreline sandstone sequence, indicating a fan delta depositional setting. Farther east and southeast in the Julcuy area, the San Mateo Formation consists of a 600-m-thick sequence of coarse-grained conglomerates similar to the lower Zapotal Formation, with imbricated polymictic clasts, debris flows, and olistoliths apparently deposited in an alluvial fan environment (Figure 11). There, the San Mateo Formation generally rests directly on Cretaceous rocks (Cayo, San Lorenzo, or Piñon formations), indicating strong pre-Bartonian erosion and a conspicuous basal unconformity. In the entire Manabí area, paleocurrents indicate a NNW- to northwest-oriented transport (Egüez, 1985; Santos et al., 1986a; Contreras, 1990) (Figure 12).

In summary, the Bartonian–Priabonian paleogeography comprises a central area (Chongón-Colonche Cordillera, Manabí hills) marked by alluvial fan deposition (lower Zapotal and upper San Mateo formations) and reworking of Cretaceous and Paleogene rocks. These coarse-grained deposits grade westward (Manabí present-day coast) into fan delta deposits (upper San Mateo Formation) and south- or southwestward into alluvial plain systems (lower Zapotal Formation) and coastal deposits (Punta Ancón Formation) (Figure 12). This paleogeographic setting, together with the volcanic-rich nature of the deposits (Figure 13) and the locally important pre-Bartonian unconformity, clearly indicate that the Chongón-Colonche Cordillera was drastically rejuvenated near the Lutetian–Bartonian boundary and submitted to intense erosion. Late Priabonian–late Oligocene time is characterized by a widespread sedimentary hiatus (Canfield, 1966; Sigal, 1969; Bristow and Hoffstetter, 1977; Benitez, 1992).

Consequently, the Bartonian–early Priabonian time span (about 42–38 Ma, after Haq et al., 1987) is interpreted as a period of pronounced tectonic activity that culminated in emergence of the entire area during the late Priabonian. In the Santa Elena Peninsula, the late Eocene deformation resulted in open folds trending north-south to northeast-southwest associated with east-southeast gently dipping reverse faults, which indicate a grossly ESE-WNW compression associated with WNW-ward thrust movements. Such deformation has not been observed in the Neogene deposits.

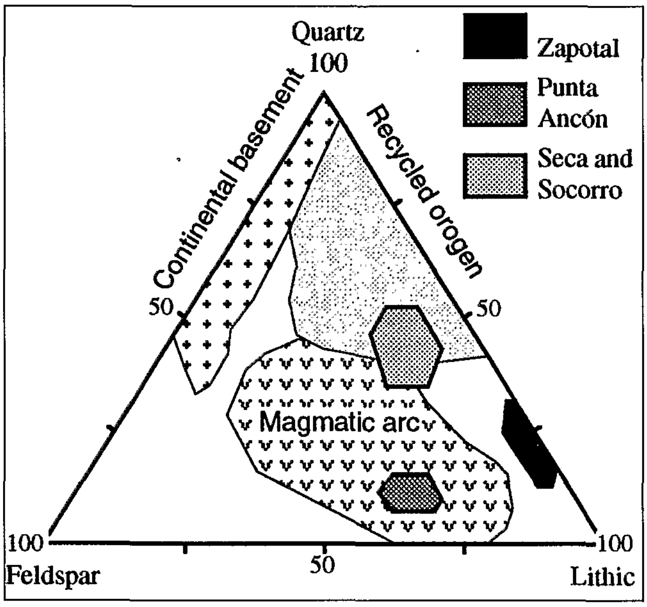

Figure 13—Nature of the detritus during the early middle Eocene (Socorro and Seca formations) and the late middle and late Eocene (Punta Ancón and lower Zapotal formations). (After Marksteiner and Alemán, 1991.)

TECTONISM AND BASIN DEVELOPMENT

The Late Cretaceous–late Eocene evolution of coastal Ecuador reflects three phases that were separated by major tectonosedimentary events (Figure 14).

Marginal Basin Stage: Late Cretaceous–Middle Paleocene

Between the Late Cretaceous and middle Paleocene, volcaniclastic pelagic sediments accumulated on the Early–middle Cretaceous oceanic floor of southern coastal Ecuador. The lack of significant quartz-rich detritus suggests that they were not deposited from a sialic landmass. The presence of a thick coarse-grained sequence of Santonian–Campanian age (Cayo Formation) suggests that the basin was bordered by an island arc, active at least since the Coniacian. The fining-upward trend of this sequence indicates that the activity of the Cayo arc decreased with time. In contrast, volcanic and tectonic activity since the late Campanian in the Manabí area (San Lorenzo Formation) is interpreted as resulting from the formation of a new island arc. Therefore, we interpret the Late Cretaceous–middle Paleocene sequence as the infilling of a marginal basin (Karig and Moore, 1975) opened between the early Late Cretaceous Cayo arc and the San Lorenzo island arc active in latest Cretaceous–early Paleocene time (Figure 14). According to the models of Karig and Moore (1975) and Carey and Sigurdsson (1982), the significant alteration and metamorphism of the Early Cretaceous volcanic rocks (Piñon Formation), the presence of hyaloclastites at the base of the sequence near Guayaquil, and the apparent lack of Cenomanian–Coniacian deposits (Calentura Formation) in the Manabí region are consistent with this interpretation.

Accretion and Early Fore-Arc Basin Stage: Late Paleocene–Early Eocene

The late Paleocene–early Eocene was marked by the occurrence of major tectonism that caused drastic changes in the paleogeography (Figure 5, 14). The nature of the coarse-grained detrital deposits indicates that sialic, sedimentary, and volcanic provenance areas were intensely deformed and deeply eroded. The differences in the tectonic and sedimentary evolutions of the Santa Elena Peninsula and the Chongón-Colonche-Manabí area indicate that they represent independent structural units during the Paleocene–early Eocene deformation phases (Figure 14).

In the Santa Elena Peninsula, intense deformation of the middle Paleocene Santa Elena Formation is followed by substantial tectonic subsidence that accommodated deposition of thick uppermost Paleocene coarse-grained, *quartz-rich turbidites* (Azúcar Group) (Figure 14). North of the Chongón-Colonche fault, this tectonic phase is believed to have induced the sedimentary hiatus of latest Paleocene–early Eocene age. Although the early Eocene period is still poorly understood, it is apparent that the Santa Elena Peninsula became emergent at this time. These events are interpreted as the result of collision of the Cayo remnant arc with the continental margin, which provoked the blocking of the subduction and probably the thrusting of the Chongón-Colonche Cordillera and Manabí areas (Figure 14). The shallowing-upward sequence of latest Paleocene–early Eocene age represents the infilling of the first real fore-arc or slope basin in southern coastal Ecuador history.

In the Talara basin, which formed above the Amotape massif of northwestern Peru, the Paleocene–Eocene boundary coincides with a thick unconformity-bound succession of continental derived sandstones and conglomerates (Mogollón Formation) (González, 1976; Macharé et al., 1986; Séranne, 1987). This unconformity clearly expresses a second important tectonic event of earliest Eocene age that we correlate with the widespread sedimentary hiatus observed in southern coastal Ecuador. These accretionary events, of late Paleocene and earliest Eocene age, mark the end of the island arc marginal basin evolution in southern coastal Ecuador.

Fore-Arc Basin and Definitive Collision: Middle–Late Eocene

The middle–upper Eocene sedimentary strata of marine shelf and terrestrial origin are characterized by a marked shallowing- and coarsening-upward trend (Figures 5). This period ended with a major sedimentary-stratigraphic hiatus, which encompassed most of the Oligocene.

The early Lutetian transgression is attributed to extensional processes. This interpretation is supported by

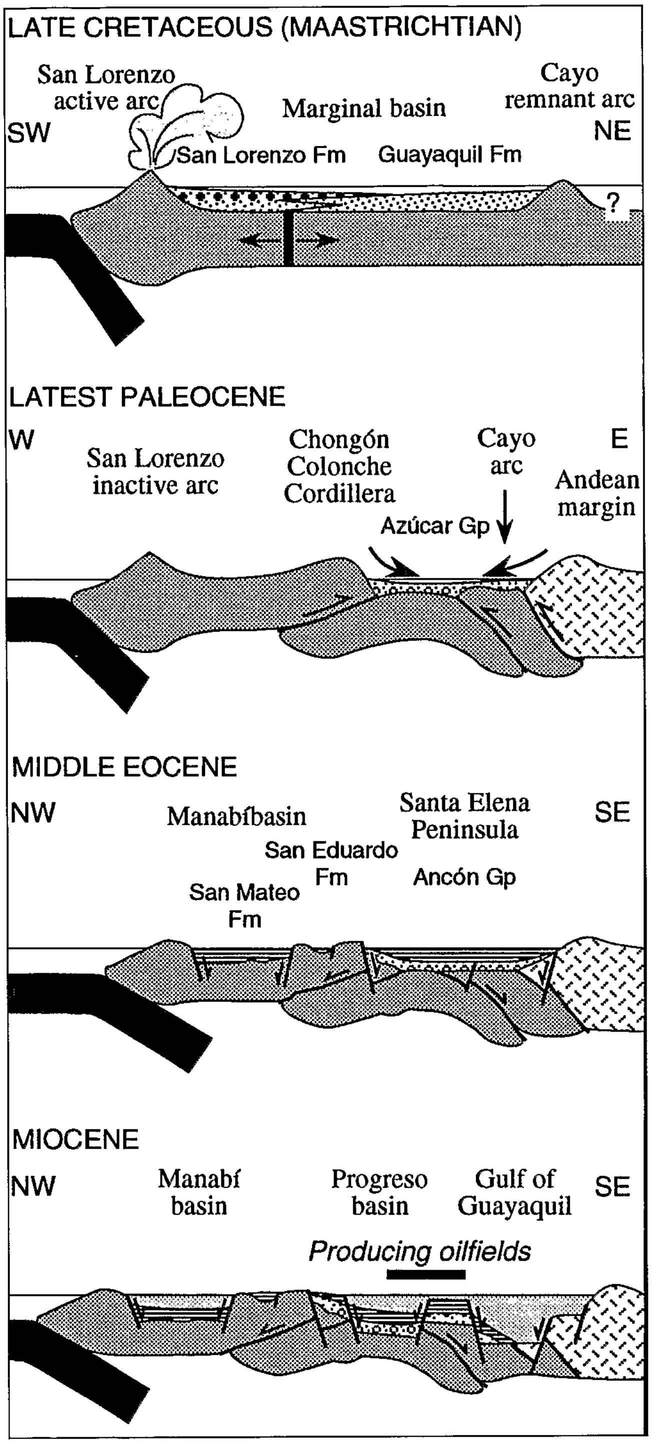

Figure 14—Schematic cross sections showing the evolution of southern coastal Ecuador from Late Cretaceous to Miocene time. (Rotations are not taken into account.) (a) In the late Cretaceous, a marginal basin opened between the early Late Cretaceous Cayo arc and the latest Cretaceous–Paleocene San Lorenzo island arc. (b) In the late Paleocene–earliest Eocene, the Cayo remnant arc collided with the Andean continental margin and caused intense deformation of the Santa Elena Peninsula, emergence of the Chongón-Cordillera, and infilling of the Santa Elena basin by coarse-grained turbidites. (c) Middle Eocene time was characterized by the extensional subsidence of fore-arc basins, which were deformed and probably inverted during the late Eocene compressional phase. (d) Following a general emergence phase of latest Eocene–Oligocene age, new extensional fore-arc basins were formed as the Gulf of Guayaquil opened.

persistent reworking and slumping, pronounced diachronism of the transgression, local pre-Lutetian erosion, and upward disappearance of the synsedimentary deformation. This extensional driven transgression following the early Eocene compression marks a renewed stage of fore-arc basin subsidence in southern coastal Ecuador (Figure 14). The differences in the Lutetian evolution and lithologies observed on either side of the Chongón-Colonche fault suggest that the Santa Elena basin was separated from the Manabí basin by the Chongón-Colonche Cordillera swell. These fore-arc basins were filled by the middle–upper Lutetian shallowing-upward sequence.

The paleogeographic change expressed by the basal unconformity and the volcanic-rich and coarse-grained nature of the Bartonian–Priabonian deposits are interpreted as the result of definitive collision of southern coastal Ecuador with the Andean continental margin. The WNW-ESE compression determined for the late Eocene tectonic phase is consistent with this interpretation.

Coarse-grained Priabonian deposits comparable to those of southern coastal Ecuador occur in the surrounding areas. In northwestern Peru, unconformable lower upper Eocene conglomerates (Verdún Formation) overlap Tertiary sedimentary strata of the Talara basin (Paredes, 1958; González, 1976; Séranne, 1987) and the Paleozoic–Cretaceous rocks of the broader area (Caldas et al., 1980; Reyes and Caldas, 1987). In the Eastern Cordillera of Ecuador, which constitutes the eastern edge of the microplate of coastal Ecuador (Santos and Ramírez, 1986), the middle Eocene succession ends in coarse-grained deposits (Apagua conglomerates) interpreted as the result of collision and underthrusting of this unit under the continental margin (Egüez and Bourgois, 1986; Bourgois et al., 1990). This interpretation matches our own observations.

New Fore-Arc Basin: Late Oligocene–Miocene

The late Oligocene–earliest Miocene to Pliocene interval is marked by the development of several basins that were filled by fine-grained shallow marine sandstones and shales (Figure 14). The creation of these Neogene troughs is thought to have been triggered by the opening of the Gulf of Guayaquil along the Guayaquil-Dolores megashear (Shepherd and Moberly, 1981). In the Santa Elena Peninsula, the Neogene Progreso basin is confined by a strand of the Chongón-Colonche fault (Carrizal fault) and by the La Cruz fault (Figure 2), probably inherited from the late Paleocene–early Eocene collision (Figure 14). Their evolution is broadly contemporaneous with that of the Andean intermontane sedimentary basins controlled by a transtensional-transpressional tectonic regime (Lavenu et al., 1992; Marocco et al., 1995). Most of coastal Ecuador became emergent during the Quaternary.

CONCLUSIONS

Between the Late Cretaceous and late Eocene, the oceanic-floored allochthonous terranes of southern coastal Ecuador underwent a complex geologic evolution that included island arc related and marginal basin sedimentation, collisions associated with prominent shear deformation, basin subsidence, and several phases of uplift. The Cenomanian–middle Paleocene phase was characterized by pelagic and volcaniclastic sedimentation in a marginal basin that was remote from silicic detrital influx. Late Paleocene–early Eocene time was marked by intense tectonic deformation, voluminous silicic detrital influx, and prominent sedimentary breaks and ended with widespread emergence of coastal Ecuador. These phenomena are attributed to collision of southern coastal Ecuador with the Andean continental margin, which caused the creation of an early, short-lived fore-arc or slope basin. Middle Eocene time began with a tectonically induced diachronous transgression. This was followed by a middle Eocene shallowing-upward sequence that represents the infilling of a new, short-lived fore-arc basin. Late Eocene is marked by locally unconformable, coarser grained, shallow-marine and continental deposits. The latest Eocene emergence of southern coastal Ecuador is attributed to a major compressive event preceding the development of a new stage of fore-arc basin subsidence in the latest Oligocene–Miocene.

The late Paleocene and early Eocene tectonic phases recorded in the Santa Elena Peninsula are undoubtedly the most intense deformation episodes undergone by coastal Ecuador. The first was responsible for numerous gently dipping shear planes, subisoclinal folds, and pervasive cleavage. The second apparently formed tight vertical folds and faults. In contrast, the present-day structure of the middle Eocene beds displays only reverse faults and gentle folding with dips usually less than 30°, which are probably due mainly to the late Eocene tectonic phase. From the late Eocene onward, the Andean deformation shifted eastward in the present-day Andes toward the sub-Andean zone. However, the effects of these early tectonic phases have been largely ignored or at least underestimated in the eastern regions.

Except for Feininger and Bristow (1980), Roperch et al. (1987), and Lebrat et al. (1987), southern coastal Ecuador has generally been analyzed and interpreted from an autochthonist point of view. The recognition of numerous tectonic events during the Late Cretaceous–late Eocene clearly indicates, however, that this was a very mobile zone that underwent various types of translation and rotation (Roperch et al., 1987). Scholl et al. (1980, p. 568) noted that "lateral tectonic accretion can create a geographically wide ocean margin of exceptional structural, lithologic and stratigraphic complexity," and "can presumably form structural basins within which substantial thickness of shelf or slope deposits can accumulate." Southern coastal Ecuador exhibits such a complex structural and sedimentary evolution, which can be explained by a multiple accretionary history (Figures 14). The hypothesis, according to which mélange or a giant olistostrome formed during Paleogene time (Colman, 1970), has not been confirmed by our study.

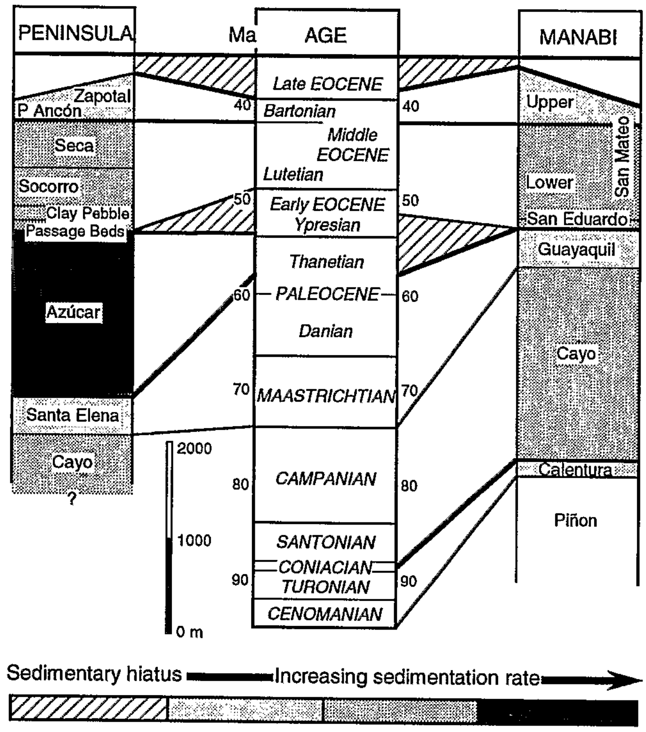

Figure 15—Estimated sedimentation rates in southern coastal Ecuador during Late Cretaceous–late Eocene time.

One striking feature of this evolution is the close association between phases of uplift and the succeeding subsidence, which created successive short-lived fore-arc basins separated by periods of erosion (Figure 15). This suggests the existence of a genetic link between compressive tectonic phases responsible for uplift and the subsequent subsidence associated with extensional tectonism. Such a relationship has been noted in the present-day margins of Japan and Peru and is believed to be due to tectonic erosion of the edge of the continental margin along the plane of subduction (Von Huene et al., 1985; Suess et al., 1988; Von Huene and Lallemand, 1990). It is inferred that during the compressive phases responsible for emergence, coupling between the oceanic and continental lithospheres increased substantially, thus provoking tectonic erosion of the lower surface at the edge of the continental margin. This loss of mass along the continental margin was sufficient to initiate tectonic subsidence of the fore-arc zone and the creation of subsiding fore-arc basins as the compressive stresses decreased (Von Huene and Scholl, 1991).

Southern coastal Ecuador is an example of small oil fields located in an accretionary fore-arc setting. The origin and evolution of the organic matter was controlled by the geologic history. The organic-rich, fine-grained deposits of Cenomanian–Coniacian and Maastrichtian–middle Paleocene age (Calentura and Guayaquil formations) form good potential source rocks for oil generation (Alvarado and Santos, 1983; Petroecuador proprietary report) and have probably sourced the oil fields of southern coastal Ecuador. These sedimentary strata were deposited in an anaerobic marginal basin isolated from silicic detrital influx, characterized by weak subsidence and low sedimentation rates.

All the producing oil fields in southern coastal Ecuador occur on the Santa Elena Peninsula (Figure 2) where there was intense deformation and substantial latest Paleocene sedimentation. The late Paleocene collision of part of southern coastal Ecuador against the Andean continental margin deformed the stratigraphic succession and allowed deposition of thick, quartz-rich arenites in the Santa Elena Peninsula (Figure 14). These deposits may have favored burial and maturation of the organic matter, since the occurrence of oil fields in southern coastal Ecuador coincides with the paleogeographic extent of the upper Paleocene turbidites. Moreover, in the Ancón oil fields, the uppermost Paleocene beds, which are called the Atlanta sandstone, represent the main reservoir interval, whereas the middle Eocene clastics provide thin secondary reservoirs. However, the alternation of periods of high sedimentation rates (latest Paleocene and Lutetian) with periods of nondeposition and even emergence and erosion (early and late Eocene) (Figures 14, 15) probably disturbed maturation of the organic matter.

Finally, the late Paleocene, early Eocene, and middle Eocene tectonic phases recorded in the Santa Elena Peninsula have significance for exploration. The intense cleavage of some Cretaceous–Paleocene volcanic and volcaniclastic rocks resulted in pronounced fracture porosity which has enhanced reservoir potential, such as the small Santa Rosa–Petropolis oil field west of Santa Elena. Thermal perturbations and weak metamorphism related to early tectonic events may have also modified and helped the organic maturation process. Although the geometry of the large-scale thrust planes cross cutting the deformed pre-Lutetian beds is still virtually unknown, it undoubtedly controlled the migration and trapping of hydrocarbons in the Santa Elena Peninsula. Finally, reverse faulting of probable late Eocene age that cross cut the older structures is responsible for east- to southeast-dipping tectonic slices, within which small reservoirs have been preserved.

Acknowledgments *This work is a contribution to IGCP 301 "Paleogene of South America." We acknowledge Petroecuador for permitting the publication of this study, and ORSTOM for having supported field work. We are grateful to A. Alemán, G. Laubacher, G. Mascle, and P. Roperch for having shared their experience of Andean and active margin geology during joint field work. The final content of this manuscript was considerably improved by a thorough review by D. Scholl and stimulating discussions with G. Mascle.*

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