

Upper Eocene Limestones, Associated Sequence Boundary, and Proposed Eocene Tectonics in Eastern Venezuela

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ABSTRACT

The Tinajitas and Peñas Blancas Limestones are thin bioclastic carbonate units of Eocene age in the foreland fold and thrust belt of eastern Venezuela. They represent the only limestone deposits in the otherwise siliciclastic Cenozoic succession of the eastern Venezuelan shelf. The geometry of the carbonate units suggests a coast-parallel, bar-like form; the particle population (larger benthic forams, glauconite, and algal balls) indicates shallow-marine provenance; and there is a regional unconformity with major lacuna landward from the location of the limestone units. We interpret these carbonates as the capping deposit of a coast-parallel ridge on the continental shelf that rose and sank in the Eocene. We propose that this transient ridge was an elastic forebulge that migrated landward across the shelf and craton hinge of the South American continent because of a brief episode of Eocene subduction of northern South American lithosphere. Such subduction may have been caused by closure between the North and South American plates. The bulge had an amplitude of at least 800 m and migrated landward at least 50–100 km. This distance suggests the minimum closure between the plates at the subduction zone. Supporting evidence comes from facies suites of the passive-margin wedge, now juxtaposed in the thrust and fold belt. The most seaward facies suite contains no evident Eocene lacuna or limestone; these facies were at too great a depth for the passing bulge to affect sedimentation. In the shallower intermediate facies, which contains the Tinajitas–Peñas Blancas Limestones, the passing ridge brought the seabed to depths of carbonate production, but not to shoal. In the most landward facies of the passive-margin wedge and on the platform, the ridge caused emergence and erosion, producing the Eocene unconformity of large coast-parallel extent. The resubidence of the margin in the Oligocene is attributed to passage of a foreland basin, which trailed the forebulge.

INTRODUCTION

Among the debates that have characterized sequence stratigraphy through its history, and continue to this day, is the question of controls on relative sea-level change and the development of regional unconformities. The concept of eustasy (Vail and Mitchum, 1977; Haq et al., 1987) as the predominant driver of relative sea-level change certainly had great initial appeal, but it has been challenged repeatedly and refined (Sloss, 1991; Miall, 1991, 1992). Contributing to this effort have been a number of studies focused on the recognition of changes in accommodation as a result of causes other than eustasy, such as tectonics and climate-induced sediment supply (e.g., Williams and Dobb, 1991; de Boer and Smith, 1994). Of particular relevance to this study are the conclusions of Cloetingh et al. (1985, 1989), Peper (1994), and others who have proposed that tectonic stresses may cause regional tilting and/or flexure of the lithosphere on a scale sufficient to produce stratigraphic expressions of relative sea-level change. In this paper, we interpret the development of an isolated Eocene carbonate platform and associated regional unconformity in northern Venezuela to reflect a low-amplitude flexure resulting from regional plate kinematic stresses.

We studied sections containing the Eocene Tinajitas and Peñas Blancas Limestones in the deformed foreland of eastern Venezuela (Figures 1–3) with goals of understanding their implications for sea-level changes in the Paleogene and developmental processes of a regional Eocene unconformity. We have searched, in particular, for evidence of whether Eocene tectonics were active in such processes. The two limestones, now in discrete outcrop belts but almost certainly correlative, provide critical information on the depositional record because they are the only carbonate-framework strata in the Cenozoic succession of the foreland fold and thrust belt. Our investigation includes field study of stratigraphy and structure, petrography, nanofossil dating by K. von Salis (personal communication,

1995) and foram dating by W. Sliter (personal communication, 1995) of sections in and south of Puerto La Cruz and at La Pedrera near Clarines (Figure 3). It builds on a prior petrographic and paleontologic study by Galea (1985).

A principal finding is that the Tinajitas and Peñas Blancas Limestones are bioclastic lag deposits, not reefs as sometimes assumed (e.g., Sams, 1995). Another is that the limestone successions appear fully preserved, gradational with clastics above and below, and do not show evidence of having emerged in the Paleogene. We interpret the paleogeography and bathymetry of the limestones in a context of regional facies suites to imply deposition and preservation on one or more tectonic ridge crests that rose, and then subsided without subaerial exposure. Such ridges may record a brief episode of plate boundary convergence in the late Eocene. This interpretation first was presented based on preliminary results of this study by Sageman and Speed (1997). The hypothesis of a migrating forebulge in the Eocene also has been discussed by Luna et al. (1997) and Pindell et al. (1998).

REGIONAL SETTING

The Eocene limestones occur in the deformed foreland of the Caribbean–South American plate boundary zone (pbz) in scattered outcrop belts over a 300-km strike-length in eastern Venezuela (Figures 1–3). Such belts occupy generally continentward positions in the pbz and in the 40- to 100-km-wide deformed foreland, whose landward margin is a frontal thrust

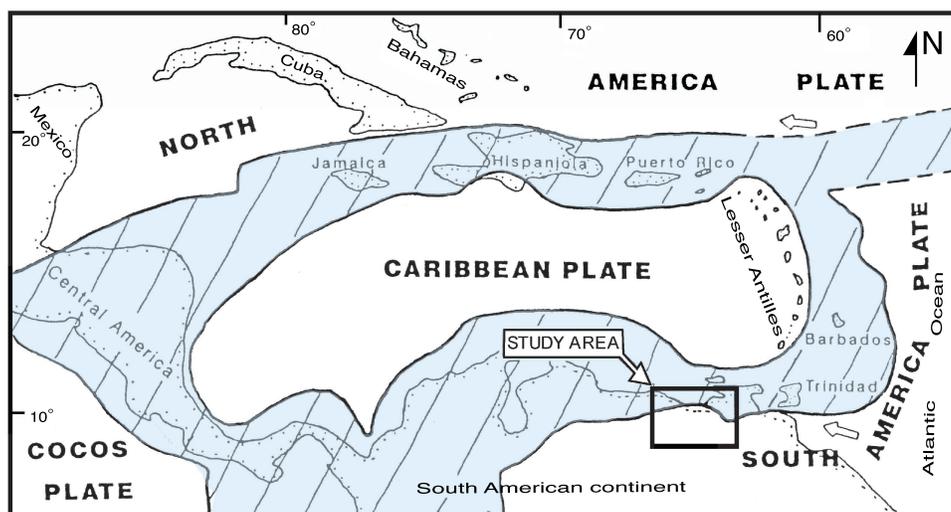


Figure 1. Map showing major tectonic plates, plate boundary zone (crosshatched), and location of study area. Arrows indicate relative plate motion of North and South American plates.

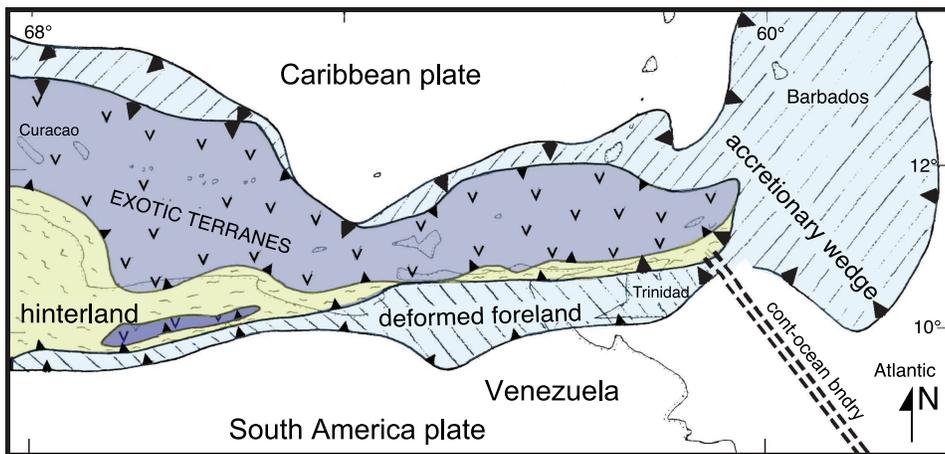


Figure 2. Detail of study area showing plate boundary zone belts, including accretionary wedge, exotic terranes, hinterland, and deformed foreland.

(Figure 3). Landward of the frontal thrust is the autochthonous foreland, which is marked by the Temblador facies suite (Figure 3; see below).

PLATE BOUNDARY ZONE

The contemporary velocity of the Caribbean relative to the South American plate in eastern Venezuela is east, 2 cm/yr (Weber et al., 2001). Such motion appears to be concentrated on right-slip faults near the northern boundary of the deformed foreland (Franke et al., 1996; Weber et al., 2001). Many studies indicate, however, that during the Neogene, the pbz evolved by right-oblique convergence and that interplate motions were taken up over a broad zone, as much as 300-km-wide (Speed, 1985; Pindell and Barrett, 1990; Russo and Speed, 1992; Algar

and Pindell, 1993; Avé Lallemant, 1997; Speed and Smith-Horowitz, 1998). Exotic terranes and hinterland schists of this zone (Figure 2) were emplaced in a south-to-southeast direction against and above the South American continental margin. The hinterland schists are interpreted to contain Mesozoic stratal and basement precursor rocks and to have been metamorphosed and transported across the continental margin in the Neogene (Speed et al., 1997). The

deformed foreland is the thin, nonmetamorphic leading edge of the plate boundary zone. In contrast to the moderately well-understood effects of Neogene plate tectonics on eastern Venezuela, the effects of Paleogene plate tectonics, if any, are little recognized and constitute one focus of this paper.

DEFORMED FORELAND

The deformed foreland comprises a Neogene fold and thrust belt and piggybacked foreland basins. It spans a 40- to 100-km width between a frontal emergent thrust on the south and a complex of faults on the north that record late Neogene overriding of the foreland by hinterland schists (Figure 3) (Speed, 1985; Speed et al., 1997). At its southern edge, the fold and thrust belt is actively propagating into the autochthonous foreland basin by blind thrusting and incipient folding (Roure et al., 1994; Parnaud et al., 1995).

The fold and thrust belt is thin skinned, as inferred from the absence of basement rocks and of metamorphism (Bell, 1968; Beck, 1986; Rossi et al., 1987). The structure in the belt varies with position. In the eastern half, which we have studied, the belt is chiefly an upright fold train broken by reverse faults in the southern two-thirds. In the northern third, folds and

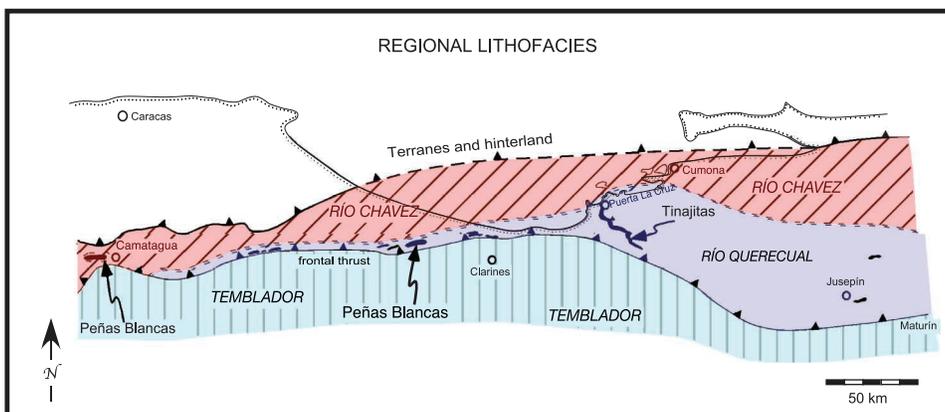


Figure 3. South American foreland: foreland thrust belt, regional lithofacies divisions, and outcrop/subcrop distribution of Tinajitas Limestone (near Puerta La Cruz) and Peñas Blancas Limestone (near Camataqua).

faults are typically flat, and the rocks occupy a set of subhorizontal nappes. Roure et al (1994) estimated total displacement among exposed strata of the eastern half of the belt at 100 km, giving a minimum width of prethrust strata of 200 km. The actual width, however, probably exceeds this for two reasons. First, the northern edge of the foreland (thin-skinned) fold and thrust belt is undefined and north of the present northern boundary. This is because of the uncertain magnitude of tectonic overlap of hinterland schist across the northern foreland. Second, the positions below the thrust belt of footwall cutoffs of Cretaceous horizons are unknown, thus permitting thrust-belt motions to include a bulk translation. As suggested below, regional facies suites imply the fold and thrust belt developed by mainly break-forward, continentward displacement. Thus, restoration of the paleogeography of strata of the deformed foreland is uncertain chiefly in the distance of transport but not their relative lateral order.

In the eastern half of the deformed foreland, structures recording permanent deformation appear to be wholly Neogene, as observed by previous authors (e.g., Roure et al., 1994) and ourselves. In contrast, structures in the far-western part of the deformed foreland record both pre- and post-Miocene deformation (Beck, 1986).

PASSIVE MARGIN

A basic premise is that Cretaceous and Paleogene strata of the deformed foreland were deposited on a north-facing passive margin of continental South America, as conceived by many authors following Maresch (1974) (e.g., James, 1990). Contemporaneous strata in the autochthon south of the deformed foreland are platformal and were deposited inboard of the passive-margin hinge. The hinge presumably underlies the fold and thrust belt, but at an uncertain locus and possibly as far north as the hinterland (Franke et al., 1996). Calculations based on stratigraphic thicknesses in the deformed foreland suggest subsidence caused by cooling ended in the Eocene (Eriksen and Pindell, 1993), at which time bathymetric depths were about 2 km, as estimated with benthic forams by Galea (1985; Vidoño Formation).

Post-passive Margin

The event history of northeastern Venezuela after its passive-margin phase includes the following: (1) development of a regional unconformity in landward sections, with lacunae ranging from intra-late

Eocene in places to much of the Paleogene in others (Hedberg, 1937, 1950; Salvador and Stainforth, 1968); (2) deposition of post-unconformity Oligocene siliciclastic sediments; (3) onset of syntectonic sedimentation related to Neogene plate collision in foreland turbidite and molasse basins; and (4) Neogene deformation of the former passive margin, producing the hinterland and foreland fold and thrust belts. Events 1 and 2 frame the subject of our study and are discussed further below.

REGIONAL LITHOFACIES AND STRATIGRAPHY

The precollisional, pre-Neogene strata in the foreland (deformed and undeformed) of eastern Venezuela are divided here among three belts of different facies suites (Figures 3 and 4). This division derives from classic stratigraphic studies, such as Hedberg (1937, 1950) and the findings of more recent field studies in the internal realms of the thrust belt (Campos and Osuna, 1977; Campos et al., 1980, 1985; Macsotay and Vivas, 1985; and V. Vivas, unpublished data). The facies suite belts are irregularly margin-parallel and span the Early Cretaceous to late Oligocene. Such strata record the onset and completion of passive-margin subsidence and the ensuing Eocene unconformity and Oligocene transgression before the onset of syntectonic Miocene sedimentation.

The most continentward facies belt, Temblador, is almost entirely paralic, sandy, and siliciclastic (Figures 3 and 5). It is a south-thinning subsurface wedge

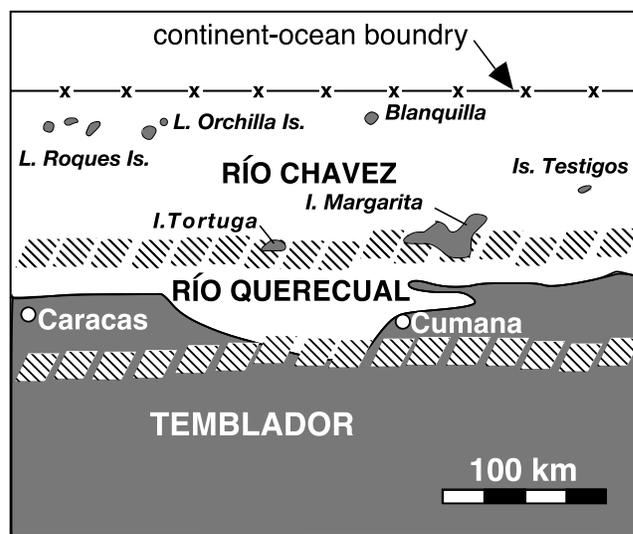


Figure 4. Areas characterized by the three facies suites (described in text) restored to possible prethrust positions. Broad transitions between these areas are indicated by crosshatched symbols.

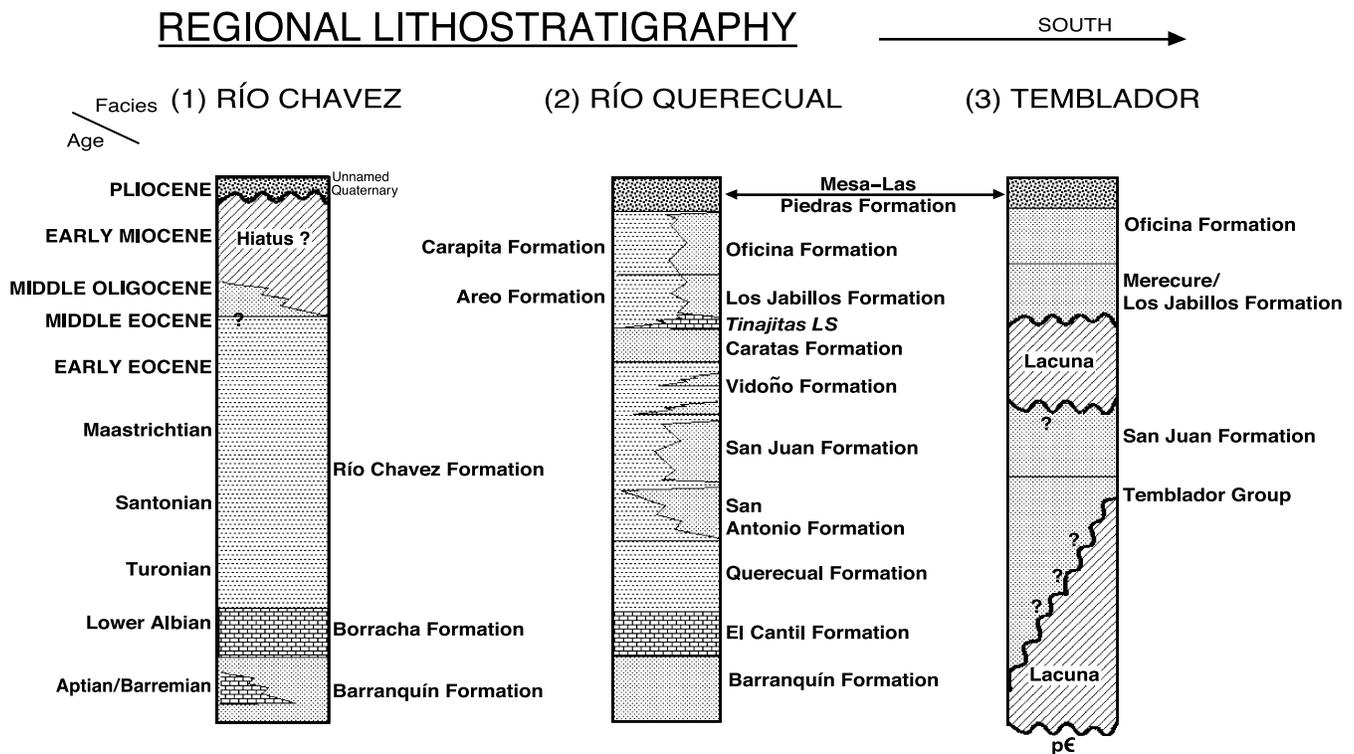


Figure 5. Generalized Cretaceous-Paleogene stratigraphic columns for the three facies belts shown in Figure 3. Lithologic symbols as in Figure 7 (plus Pliocene-Quaternary conglomerate at top).

that lies above Precambrian craton and local relics of pre-Cretaceous beds. It extends north to the front of the thrust belt and probably below that front. The Temblador facies suite is difficult to date because of the predominance of sandstone containing few index fossils.

The Río Querecual facies suite includes strata exposed in the central belt of the deformed foreland (Figure 3) and was named originally by Hedberg (1937). Such strata vary markedly in lithic type through the section (Figure 5). They record Early Cretaceous paralic conditions, deep-marine shelf in the Late Cretaceous and Paleocene, and rapidly changing environments in the Eocene and Oligocene, discussed below. The boundary between the Río Querecual and Temblador facies suites is subsurface and poorly located; alternative possible positions are (1) in the autochthon below the buried thrust front; (2) in the autochthon well north of the thrust front; and (3) in the thrust belt between exposures and the buried frontal thrust.

The northernmost of the three belts of facies suites is the Río Chavez, adopted from studies by Campos et al. (1980), as well as Macsotay and Vivas (1985). The Río Chavez includes paralic Lower Cretaceous strata and is richer in carbonate framework rocks

than the other facies suites (Figures 3 and 5). Its Upper Cretaceous and Paleocene strata are chert and radstone-rich, and less marly and lithologically diverse than those of the Río Querecual. Further, the upper Paleogene of the Río Chavez, preserved in only a few erosional remnants, has an open-marine, pelagic aspect similar to the underlying strata. Rocks of the Río Chavez facies suite are probably thrust above those of the Río Querecual belt, although the preponderance of covered ground permits a gradational contact to exist widely.

We assume the belts of the three facies suites of the deformed foreland initially were contiguous and approximately margin-parallel. The belts can be retrofit using the southeast-to-south displacement trajectories and 100% contraction for the northern two belts discussed earlier (Figure 4). As noted, each of the belts initially may have been wider than that shown in Figure 4. Each facies suite was deposited on continental crust, as indicated by contents of basal paralic quartz sandstone. We interpret the Upper Cretaceous and Paleogene differences among the belts to reflect northward increase in mean-water depth and open-marine environment and decrease in terrigenous sediment influx. Such interpretations accord well with expectations of sedimentation on a

cooling, north-thinning wedge of rifted and diked continental crust.

Eocene Unconformity

An unconformity of later Eocene age has been identified in parts of the entire east-west span of onland Venezuela between the Andes and the east-facing Atlantic margin (Bell, 1968; Beck, 1986; Hedberg, 1950; Veeken, 1983; Prieto, 1987). Its existence and character vary among the three belts of facies suites (Figures 5 and 6). It is a ubiquitous unconformity with substantial missing section in the Temblador facies, patchy and with minor lacunae in the Río Querecual facies, and unrecognized in the Río Chavez. We emphasize that the meager preservation of the younger Río Chavez beds gives a poor sample of that facies suite.

In the more inland realm of Temblador, the lacuna is large, extending from horizons in the Cretaceous to a poorly dated overlap of late Oligocene or Miocene sandstones (Merecure or Oficina Formations). Northward, the Temblador has less missing section, and in a few wells, the subunconformity section includes marine strata as young as middle Eocene (Arnstein et al., 1985). Such occurrences imply that passive-margin subsidence extended inland at least past the northern half of the Temblador, that the unconformity is erosional, and that erosion began in the middle Eocene or later.

In the Río Querecual facies, our studies indicate that no unconformity exists where the section contains the Tinajitas or Peñas Blancas Limestones (Figure 5). At places where these are absent, a unconformity with small lacuna may or may not exist in a poorly dated sandstone succession (Caratas Formation overlain by Los Jabillos or its western equivalent, the La Pascua Formation) between middle Eocene and middle Oligocene mudrock units (Vidoño Formation below and Areo above, or its western equivalent, the Roblecitos Formation).

We also examined stratigraphic units above and below the horizon of expected unconformity in the Río Querecual facies for differences or gradients in tectonic meso- and microstructure between

Puerta La Cruz and the frontal thrust (Figure 6). There is no structural contrast, and units above and below have had the same structural history. This implies that if an unrecognized Eocene unconformity exists, its development included no horizontal contraction or extension.

The Río Chavez facies suite contains good evidence by dated successions that an Eocene unconformity is absent. Such sections indicate, moreover, that the pelagic environment of deposition prevailed through the Eocene and early Oligocene (Campos et al., 1980, 1985; V. Vivas, unpublished data). The main uncertainty with the Río Chavez is poor spatial sampling as a result of sparse preservation or exposure of section as young as Eocene.

PALEOGENE STRATIGRAPHY OF RÍO QUEREQUAL FACIES SUITE

The Tinajitas and Peñas Blancas Limestones, the focus of our study, are laterally extensive thin sheets (<30 m) of probable middle Eocene but possibly slightly younger age. They occur in the Río Querecual facies suite and are the only carbonate framework units of Late Cretaceous or Paleogene age in eastern Venezuela. Figure 3 shows their outcrop distribution, together with two sites to the east where comparable Eocene limestone may exist in wells. The two limestone bodies exist discretely on strike in the thrust belt. Because of their nearly identical lithic character and fossil content, they are almost certainly correlatives and likely to have been contiguous initially, as

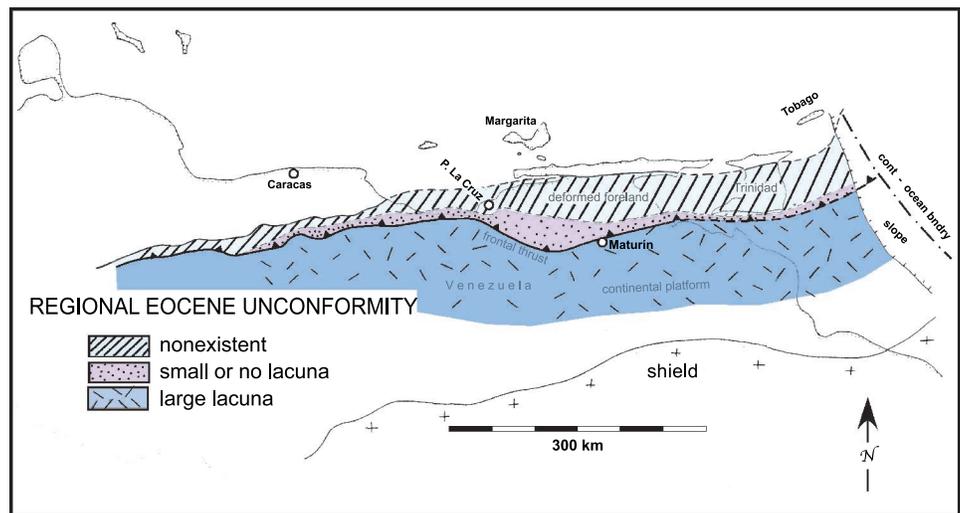


Figure 6. Map illustrating the distribution and character of Eocene unconformity in the study area showing progressive southward increase in lacuna.

earlier proposed by Salvador (1964) and Galea (1985). We now briefly discuss the physical stratigraphy of the Paleogene succession of the Río Querecual facies suite, noting that names used for some intervals at and east of Puerta La Cruz (as used in Figure 5) differ from those to the west.

The Paleogene succession begins with the siliciclastic, muddy, and partly turbiditic Vidoño Formation of Paleocene to middle Eocene age. Benthic forams were interpreted by Galea (1985) as indicating a depositional depth of about 2 km for at least the upper Paleocene part of the Vidoño near Puerta La Cruz. The lower Eocene Vidoño may have been even deeper. In our view, the Vidoño contains the deposits of the most subsident phase of the passive-margin wedge, some 70–80 m.y. after onset.

The Vidoño is overlain gradationally by 300 m of an upward-coarsening succession from mud-rich to mud-poor beds of the Caratas Formation. Its lower beds include classic turbidites, whereas the upper half is more massive and amalgamated fine- to medium-grained sandstone. The Caratas is undated. Its sand population comprises quartz, glauconite, and minor skeletal components, the latter consisting of broken, worked particles and whole benthic and planktic forams. The proportion of glauconite and skeletal particles increases upsection to a constant 50% in the upper quarter. The bathymetry of the Caratas is uncertain. The unit almost certainly represents a sand-rich progradation above the basinal Vidoño.

The Tinajitas and Peñas Blancas limestones both conformably and gradationally overlie the Caratas with the contact defined by abrupt increase in the proportion of skeletal particles relative to quartz and glauconite (see below). Moreover, both limestones are gradational to overlying sandstone units, which are called Los Jabillos to the east and La Pasqua to the west. The top of the Tinajitas Limestone is defined by a crusty red layer 1-m thick, referred to as a laterite by Galea (1985). We argue below that the crusty red top is a zone of concentrated dissolution and joint development, not a sedimentary laterite. This zone is postdepositional and crosses the gradational boundary from the limestone into skeletal-poor quartz-glauconite arenite of the overlying Los Jabillos Formation. The Peñas Blancas Limestone is overlain with sharply gradational contact by 6 m of glauconite-quartz-skeletal arenite. This contact is locally freshly preserved but highly altered at places along strike. The altered material is crusty red rock in the walls of steep joints and normal faults that cut both the suprajacent arenite and the Peñas Blancas.

The Los Jabillos Formation is a sandstone-rich unit without dateable fossils between the overlying muddy Areo Formation and underlying Tinajitas Limestone (Figure 5). Where the Tinajitas is absent, Los Jabillos is distinguished from the Caratas Formation either arbitrarily or at zones of coarsening upward or diminishing glauconite contents in sandstone successions. Physical evidence for an unconformity between the two is lacking, unless the absence of Tinajitas is so taken. Regionally, section mapped as Los Jabillos varies markedly in thickness, from a few to hundreds of meters. Characteristics of the La Pasqua Formation are similar to those of the Los Jabillos.

The Areo Formation lies above the Los Jabillos Formation in the Puerta La Cruz region (Figure 5). It is a basinal siliciclastic mudstone-sandstone succession of variable thickness, from tens to hundreds of meters. Dating by planktic fossils (K. von Salis, personal communication, 1995) indicate that the Areo is Oligocene, with its base either in the early–late Oligocene or early Oligocene (see below). West of Puerta La Cruz, the muddy Roblecito Formation of Oligocene age lies above the La Pasqua.

VIA ALTERNA AND LA PEDRERA SECTIONS

We examined the details of the Tinajitas and Peñas Blancas Limestones and immediately enclosing siliciclastic strata at two sites of good exposure: the Via Alterna roadcut south of Puerta La Cruz and the La Pedrera Quarry near Clarines (Figure 3). The sections are similar, and we refer to our stratigraphic column of the Via Alterna section in Figure 7.

Enclosing Siliciclastic Strata

At both sections, the Caratas Formation in the 10 or so meters below the limestones is massive, fine-to-medium-grained, well-sorted, quartz-glauconite sandstone with increasing proportions of skeletal particles (benthic forams, algal debris) toward the limestone base. The sandstones are burrowed, and many tubes descend from the limestone contact. The massivity and skeletal content of the uppermost Caratas may be products of bioturbation. The Caratas-limestone contact is marked by an abrupt and conformable increase in proportion of skeletal particles.

Above the Tinajitas Limestone, the Via Alterna section contains 26 m of medium- to coarse-grained sandstone (Los Jabillos) surmounted by more than 130 m of interlayered mudstone and sandstone (Areo) (Figure 7). The Los Jabillos is variably massive, plane laminated, and cross laminated with low-angle

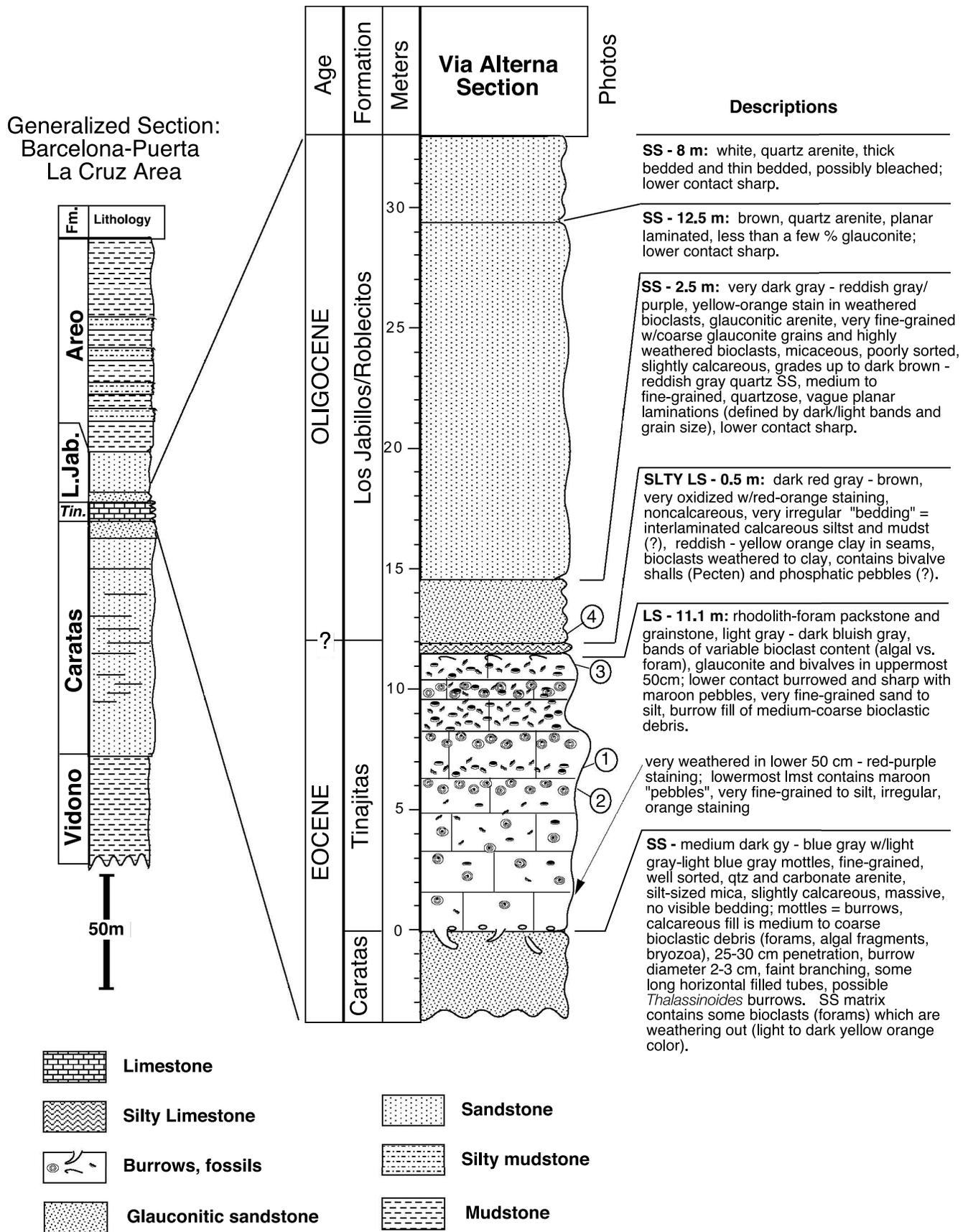


Figure 7. Generalized lithostratigraphy of Barcelona-Puerta La Cruz area with detailed section description of Tinajitas Limestone at Via Alternata. The stratigraphic horizons corresponding to thin-section micrographs in Plate 1 are indicated.

planar foresets. The sand-particle composition grades upward from 45% glauconite, 45% quartz, and 10% skeletal material to 100% quartz. The Areo consists of 5–15-m-thick sets of beds of fine-grained quartz sandstone and mudstone, which collectively fine and thin upward. Some sets have scoured bottoms. Some beds are graded, but there are few classic turbidites. K. von Salis (personal communication, 1995) obtained late Oligocene (NP24) ages from nannofossils found in samples near the highest exposures. Benthic microfossils in the Areo are solely arenaceous forams, suggestive of deeper water, according to Galea (1985, and personal communication, 1995).

The Areo Formation at Via Alternata is considered a basinal deposit by virtue of its sparse nannofossils and arenaceous benthic forams, absence of calcareous forams, and high proportion of mud. The preservation of sand-mud multilayers implies rapid subsidence or (and) subwave base deposition. The thicknesses of the Areo and Los Jabillos Formations appear to vary geographically with an inverse relation. Taken together, such inferences suggest that the two formations may compose a diachronous sequence deposited on a transgressional subsiding margin.

The quarry at La Pedrera includes about 30 m of section above the gradational top of the Peñas Blancas Limestone. Of this, the lowest 3 m is a massive glauconite-quartz-skeletal arenite (50% glauconite, 45% quartz, 5% skeletal). This grades up to glauconite wacke in which glauconite and minor quartz sand floats in a siliciclastic mud matrix (3-m thick). Above that is black mudstone of the Roblecito Formation. The sandy basal 6 m would be considered either basal Roblecito or a tongue of the La Pascua Formation. At La Pedrera, we obtained nannofossil ages of late Oligocene (NP24) for Roblecito mudstone and subjacent glauconite wacke (K. von Salis, personal communication, 1995). An early Oligocene foraminiferal age (*Pseudohastigerina micra* zone) was obtained by Galea (1985) from black mudstone above Peñas Blancas Limestone at or near La Pedrera.

To summarize, the Paleogene sections containing the Tinajitas and Peñas Blancas Limestones begin and end in basinal dark siliciclastic mudrock (Figure 7). The beginning depositional depth is substantial (approximately 2 km); the final depth also is deep but inexact. The intermediate phase was the deposition of sand with symmetric distributions of particle composition and size about the median limestones. The duration of the succession is about 20 m.y., and limestone deposition may have been

midway or a little beyond. It is unfortunate that we have no direct gauges of bathymetry or rates of deposition in the section. There is, however, no physical evidence for hiatus or lacuna associated with the limestones.

Tinajitas and Peñas Blancas Limestones

As noted, the Tinajitas and Peñas Blancas Limestones are each thin tabular sheets that are structurally discrete, probably contemporaneous, and possibly originally contiguous. Each is < 20-m thick; the variability in current thickness, 0–20 m, is partly or wholly structural, and it is unclear whether there is a depositional variability on strike.

Composition

Both formations are calcarenite (skeletal grainstone and packstone) that varies from medium- to very-coarse-grained. They are uniformly plane stratified by orientation of nonequant particles and are bedded by vertical variability in size ranges and proportions of particle types. The beds are relatively homogeneous and abruptly gradational. There is no systematic distribution in beds by particle size or density. The units contain no boundstone, no discrete mudrock, and no evident erosion surfaces. Sections appear laterally uniform over strike lengths of exposure, which are individually less than 200 m.

Particle types in the limestones include carbonate, quartz, and glauconite. The major carbonate components (Plate 1.1 and 1.2) are benthic foraminifera (chiefly *Lepidocyclina*) and *Melobesioid* algae (especially algal balls) (Galea, 1985). Secondary components include thick shells of bivalves and gastropods, planktic foraminifera, and bryozoa. Each of the biogenic types is found both whole and fragmented. The benthic forams are least broken, whereas shells are the most commonly broken. At several sites, there are beds of concentrated whole oysters densely packed in coarse bioclastic matrix (Galea, 1985). The algal balls, or rhodoliths (Bosence, 1983), vary from 2–3 mm to 3–4 cm in diameter and are commonly bored. Diverse *Melobesioid* algae occurs as laminar and encrusting types (on shells), and as columnar specimens or fragments (Galea, 1985). Particle sizes in the limestones range from medium-grained sand as much as 1–2 cm in diameter. Sand-size distributions are poorly sorted and commonly bimodal—a framework of coarse particles and interstitial medium-grained sand.

The pores of calcarenites are variably microspar, glauconitic mud, or a mix of micrite and glauconitic

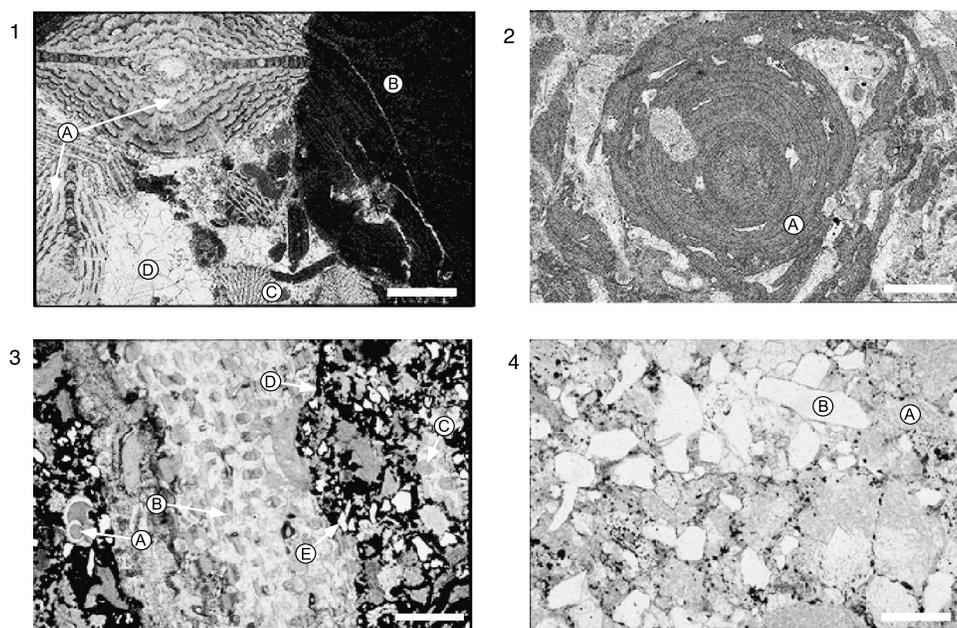


Plate 1. Thin-section micrographs of samples from Via Alterna section. Micrographs 1 and 2 show dominant bioclasts of the limestone facies: (1A) benthic foraminifera (lepidocyclinid) and (2A) rhodolith (algal ball). Also indicated are (1B) algal masses (dark), (1C) bryozoan fragment, and (1D) coarse sparry calcite filling large pore space. In micrograph 2, rhodolith (or algal ball) is marked by (A). Micrograph 3 shows example of transition from Tinajitas to glauconitic sandstone facies, including glauconitic infilling of chambers in (A) planktic (*Trunorotaloides rohri*) and (B) benthic (lepidocyclinid) foraminifera, Glauconite as grains (C) and matrix, with some zones altered to (black) oxide (D), and increasing numbers of quartz grains (E). Micrograph 4 shows example of glauconitic arenite (Los Jabillos). Dominant constituents include (A) subangular-subrounded grains of quartz and (B) green glauconite (appears gray) as grains and minor matrix. All micrographs in plane light with 1 mm scale bar.

mud. The chambers of many benthic and planktic forams are filled with glauconite (Plate 1.3). Forams with glauconite fill occur with or without the existence of matrix glauconitic mud and occur together with forams whose chambers contain no glauconite.

Aside from the occurrence of the oyster beds low in the section, the limestones contain no systematic stratigraphy of biogenic particle types or sizes. In contrast, quartz and glauconite sand are concentrated in the 1–2 m of strata directly over- and underlying the limestones, where each is a third of the sand population (Plate 1.4). Inboard of the upper and lower margins, quartz and glauconite are minor (<1%), silt-sized, and dispersed. The distribution of particle types through the Tinajitas/Peñas Blancas is represented in Figure 8.

Age

Early workers assigned both limestones to the Oligocene without paleontologic basis (Hedberg, 1937). It was thought that the limestones were basal to a transgressive sequence (Areo, Roblecito) dated by

macrofossils. Based on planktic foraminifera studied by M. Furrer, Salvador (1964) reassigned the Peñas Blancas to the middle Eocene. Galea (1985) examined the planktic forams in thin section from both limestones, identifying *Truncorotaloides rohri* and *Globigerinatheka* sp. Her identifications are corroborated from our specimens by W. Sliter (personal communication, 1997). The two species overlap in the *T. rohri* zone of late–middle Eocene age. We question, however, whether this should be taken as age of deposition because of evidence given below, suggesting resedimentation and slow deposition. The first appearance of *Globigerinatheka* sp. in the late *T. rohri* zone is thus a maximum age, and late Eocene or even early Oligocene are conceivable true ages.

Karst

Galea (1985) interpreted rocks at the top of the Tinajitas Limestone at Via Alterna to be a karst with cavern deposits of laterite. She concluded that deposition of the Tinajitas was succeeded by emergence and an erosional unconformity. Our observations lead to a different conclusion.

Karst exists in both limestone units on present ridge crests. However, such karst is Quaternary. Karst does not exist in limestone well below ridge tops, as exposed in roadcuts, quarries, or gullies.

The disputed rocks at Via Alterna are a 1-m-thick conformable layer of red, crusty earth, which does indeed resemble laterite. Close examination of this layer in the field and laboratory, however, indicates that its protolith is glauconite-quartz-skeletal arenite, which lies with sharp gradation above the top layer of Tinajitas, which is relatively glauconite- and quartz-rich. The disputed layer is, in fact, a boxwork of veinlets filled with red earth that generally are parallel and normal to the bedding. The boxwork extends up into the Los Jabillos and down into the

Tinajitas for short distances, diminishing in thickness and dying out.

The veinlets consist of cracked quartz and skeletal sand in a red iron-oxide continuum. They grade to less-altered wallrock, which is glauconite-quartz-skeletal arenite. The skeletal particles, <10%, are not resorbed in the veins. In the vein walls, glauconite commonly is coated by oxide, and the matrix includes much oxide. The boxwork evolved by jointing and by partial dissolution and oxidation of glauconite.

The boxwork is of postdepositional deformational origin because it cuts lithified rocks across the Los Jabillos–Tinajitas Formation boundary. The cracks in quartz grains are also postdepositional. The joint system must have provided a conduit for fluid throughput. Glauconite was the reactive solid; carbonate was little affected. The disputed layer, moreover, contains no depositional breccia, no evidence of cavern fill, and irregularity in thickness of altered zone, all of which would be expected with a karstic origin. The cause of jointing is unclear, but perhaps records extension of a fold limb during development of tight macrofolds.

INTERPRETATIONS

Origin of Limestones

Based on the observations described above, we interpret the following constraints on the deposition of the limestones:

- 1) Thorough mixing of diverse carbonate particles, including planktic forams of pelagic origin; algal balls of turbulent, shallow-marine bottom origin; and *Lepidocyclina*s of inner-shelf bathymetry;
- 2) two-stage deposition of many-chambered particles; first in glauconitic mud matrix and second with carbonate cement;
- 3) breakage of high proportion of carbonate particles before final deposition;
- 4) concentration of sand-sized carbonate particles reaching nearly 100% in the central 80% of the limestones, during which time the depositional sites were isolated from virtually all other particle sources and, especially, from terrigenous sources;
- 5) absence of any sedimentary evidence for deposition in deep water by sediment-gravity flow; and
- 6) no recognized hiatus or lacuna in or bounding the limestones. No evidence of scour or slump surfaces at base of limestone.

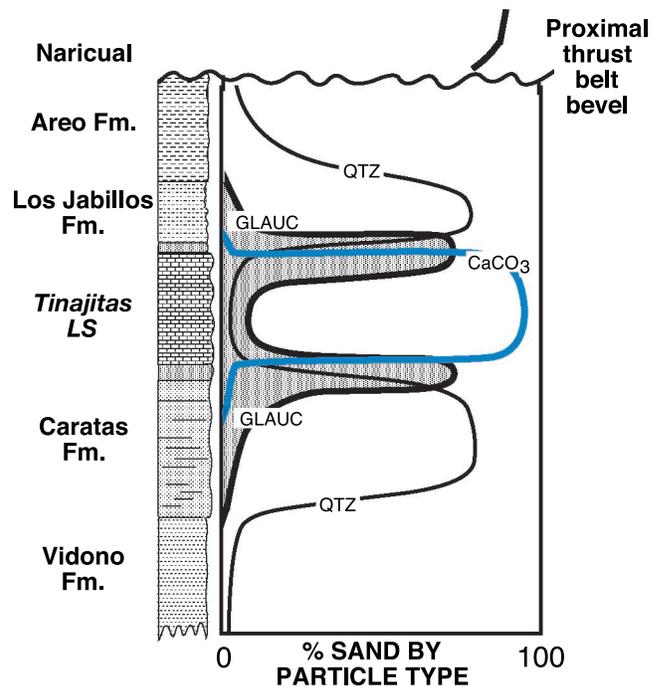


Figure 8. Distribution of particle types based on relative percentage estimates during lithologic and petrographic analyses of the study interval at Via Alterna.

We hypothesize that the limestones formed on one or a string of coast-parallel ridges or platforms that evolved in several stages (Figure 9). First, the ridge shallowed and gained enough height to isolate its crest from the supply of quartz sand to the Caratas Formation, presumably from southerly terrigenous sources (t_1 , Figure 9). At time t_1 , the ridge crest, still subwave base, received deposits only of glauconite mud, planktic fossils, and perhaps deeper-water benthics.

Second, upon further shallowing, the crest reached depths accommodating shallow-water benthics, such as *Lepidocyclina* (t_2 , Figure 9). These accumulated with other particles in the glauconitic mud layer. Third, the sea bed rose above wave base, causing the carbonate particle-mud layer to be winnowed and transformed to a lag calcarenite (t_3 , Figure 9). In this last stage, the bottom-water fluctuation permitted development of algal balls and the breakage of the detrital grains. Some clots of carbonate particles and mud matrix apparently were adhesive enough for the mud to survive the resedimentation. Most mud, however, was washed out, such that the winnowed residue was widely cemented by spar.

In a final stage, the ridge subsided relative to one or both adjacent trough, such that quartz and glauconite sand of the Los Jabillos and La Pascua Formations

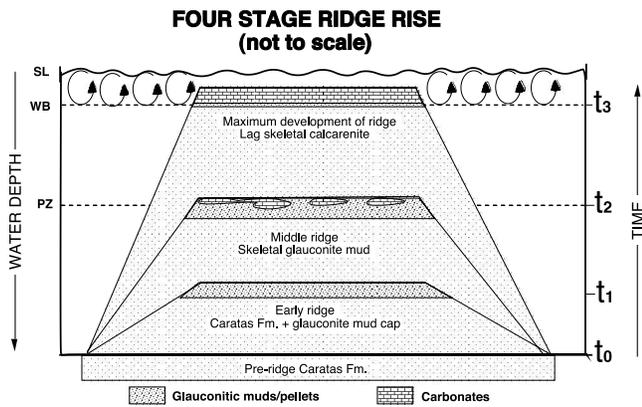


Figure 9. Model showing four stages in the rise of an elongate, shore-parallel ridge. PZ marks base of photic zone, WB marks limit of normal storm wave base, and SL marks sea surface.

overran the lag calcarenite. The former ridge crest may or may not have been lowered below wave base at this stage. Ultimately, at least, the limestone locus and the entire tract of the Río Querecual facies suite was below wave base during deposition of the Areo and Roblecito Formations.

Our interpretation holds that the loci of limestone deposition rose to shallow bathymetric depths, perhaps 100 m or less, to accommodate the growth of algae and *Lepidocylinids*. The absence of karst or other physical evidence for a capping unconformity indicates that the rise did not continue to sea level.

Model of Paleogene Bathymetric Changes

We now employ our interpretations of the evolution of the Tinajitas and Peñas Blancas Limestones and the regional Eocene unconformity in a model of Paleogene bathymetric evolution of coastal eastern Venezuela.

First, consider the height of sea-bed change from the end-Paleocene Vidoño Formation (2 km) to the limestone (in range of wave base). This is a minimum of 1.5 km and probably greater. The change includes 300 m of Caratas Formation (average regional thickness: Hedberg, 1937, 1950), and a generous 300 m for the Eocene Vidoño Formation. Allowing about 100 m for maximum Eocene eustatic changes (Haq et al., 1987), the remainder is 800 m or more. Thus, 800 m represents the minimum tectonic uplift through the early and middle Eocene (possibly longer). Differential compaction of sandy and muddy intervals of the Paleogene section is unlikely to affect this bathymetric calculation because compaction versus depth and time is known to be similar for pre-Neogene sandstone and mudstone (Baldwin and Butler, 1985).

Our sedimentological origin of the limestone invokes the rise of a coast-parallel ridge or platform, which was isolated from terrigenous sediment influx. This ridge was the rising tectonic element. It presumably had deeper-water troughs on both landward and seaward flanks (Figure 10).

The regional Eocene unconformity was related almost certainly to the events that caused deposition of the Tinajitas and Peñas Blancas. This is because the unconformity's lacuna in the Temblador facies includes the age of the limestones and its uncertainty. Further, although the existence of an unconformity in the Río Querecual facies might be indicated by the absence of Tinajitas and Peñas Blancas, we have no evidence to judge whether the absence of limestone is a lacuna or a result of nondeposition of limestone, perhaps reflecting insufficient shallowing.

The distribution of the Eocene unconformity among the three facies suites (Figure 5) in the context of a tectonic ridge can be explained if the ridge migrated progressively landward across the long Paleogene slope of the passive margin from ocean boundary to craton (Figure 10). With an amplitude of 800 m, the migrating ridge did not affect the Río Chavez facies suite, which we presume came from the deepest, most seaward half of the passive margin. Its sedimentation remained pelagic and subwave base.

The Río Querecual facies suite may have covered a relatively landward belt of the passive-margin slope. The migrating ridge may have elevated part or all of this facies belt to the photic zone, and above that to wave base, depending on the width of the ridge. The most inboard Río Querecual facies may have been elevated above sea level and subject to erosion. The modern distribution of the Tinajitas–Peñas Blancas Limestones can be explained with alternative

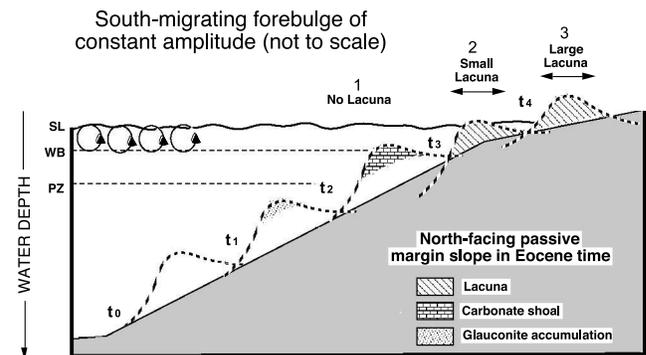


Figure 10. Interpretation of ridge as a migrating forebulge. Abbreviations as in Figure 9.

hypotheses. First, the migrating ridge was hilly, and only the hills were elevated enough to attain a cover of winnowed calcarenite. In this model, there is no unconformity in exposed Río Querecual facies. Second, the migrating ridge was hilly; winnowed calcarenite covered the entire crest, the hills on the ridge emerged above sea level, and only the valleys on the ridge escaped erosion. In this model, the Eocene unconformity is patchily widespread and has small lacuna in the Río Querecual facies suite.

Later, and farther landward, perhaps landward of the passive-margin hinge, the effect of the migrating ridge was indeed profound. The succession of Paleogene and Cretaceous paralic strata was deeply stripped. We presume the ridge ceased migration before it neared the present margin of the shield because a thin fringe of Cretaceous beds of presumably long depositional duration is preserved there.

To generalize, our model incorporates a mechanism to create local environments for the discrete generation of glauconite and biogenic carbonate. Glauconite is known to precipitate over a range of relatively shallow (shelfal) depths where the influx of terrigenous sediment is small and reworking is common (e.g., Stonecipher, 1999). We propose that the leading flank of the migrating ridge provided the required shallowing and exclusion of sediment transport from coastal and fluvial sources to the south. In our view, the flank was coated by glauconitic mud containing benthic and planktic biogenic carbonate particles. The mechanism for an isolated carbonate deposit is tectonic uplift sufficient to gain shallow wave base and concentration of particles by winnowing. Pelleting of glauconitic mud presumably occurred during winnowing, perhaps by physical accretion of low-density spheres that dropped to the sea bed downslope or by fecal processes that began after sufficient shallowing.

In addition to its effect on deposition and erosion by elevation of the sea bed in the leading half of its motion, a migrating ridge also caused second-phase effects caused by subsidence during passage of its trailing half. This presumably depressed the former shelf, following the migrating seaward slope that was the northern flank of the ridge.

The effect on deposition of such subsidence after ridge passage probably depended on the bathymetry of the concurrent ridge crest to landward. When the crest was relatively deep, deposition probably was little different from crest passage to subsidence. As the crest reached shallower depths, however, two effects were introduced. One was the generation of

new particle types: glauconite and shallow-marine carbonate, one or both of which may have been re-sedimented down the trailing flank. The second was the transfer downslope of sediment eroded from the ridge crest; here, the sediment discharge would have increased with height of the crest above shallow wave base and distance of southward migration of the crest. Such trailing flank effects would have been amplified if the ridge were followed by a tectonic downward, as in a migrating elastic fullwave (see below, "Tectonics").

Our hypothesis predicts that large northward discharge of sediment began when the ridge crest reached sea level or shortly before. Relative to our facies reconstruction, this began at a landward realm of the passive-margin slope, either in a landward belt of the Río Querecual facies suite or in Temblador. This discharge began late in the migration of the ridge crest, perhaps after 75% of its passage. The northward discharge presumably deposited on the subsiding flank, first with particles derived proximally from uppermost strata and then from more far-flung and deeply eroded sources. Thus, the Los Jabillos and basal Roblecito Formations are sandstones rich in glauconite and carrying skeletal particles, grading up to the Areo and Roblecito with general terrigenous debris.

Assuming that ridge crest passage was late-middle Eocene in the central Río Querecual facies belt, the model predicts that the Los Jabillos and basal Roblecito began deposition shortly thereafter, perhaps in the late Eocene, on a subsiding sea bed. This basal sand blanket may have been progradational or retrogradational, depending on duration and rate of late-stage ridge migration and sand bypassing through submarine canyons. The variability of thickness of Los Jabillos and the thinness and occurrence of apparently condensed sections of Los Jabillos plus Areo and of Roblecito suggests sediment bypassing in canyons.

If the postpassage sedimentation was strongly progradational, the Río Chavez facies suite should have received a cover of terrigenous turbidite fans that coarsen upward. This seems not to be the case, although the sampling is small. Thus, we assume the products of Eocene erosion either were trapped in the Río Querecual belt, which seems doubtful, or transported via canyons seaward of the Río Chavez belt to the deep-ocean floor.

Tectonics

Accepting the hypothesis of the migrating Eocene ridge, what are admissible tectonic causes? The

constraints are: parallelism to continental margin, rising then sinking, and coastal locus with landward migration. Ridge passage was not accompanied by permanent horizontal strains, at least to the resolution of our observations. Therefore, the ridge was not the front of a propagating field of horsts or thrust imbricates or an anticline above a blind thrust. The ridge must have been an elastic flexure. We propose that the ridge was the forebulge of an elastic waveform that was propelled across the South American passive margin in a brief episode of Eocene plate convergence.

The proposal employs the theory of bending elastic plates, in which a damped waveform is set up in the plate relative to a vertical load at one end. Such mechanics are applicable to forebulge-foreland basin couples that migrate toward the craton from loads supplied by overriding and tectonic thickening at convergent margins (Speed and Sleep, 1982). Assuming the flexure was a simple fullwave, the ridge in eastern Venezuela probably was the leading deflection. If so, it was followed by a tectonic trough, a foreland basin, and this may have greatly influenced the stratigraphic passage from Eocene limestone to succeeding terrigenous clastics of probable deep-water deposition. Existing data do not provide constraints on the width of the flexure or its speed. The amplitude, moreover, is poorly constrained, 0.8 km with an uncertain error of paleobathymetric estimates from benthic fossils.

The idea of a south-migrating flexure implies that an east-west striking boundary of the Eocene South American plate existed somewhere north of the present coast and that South America was the downgoing plate. The vertical load was the weight of the overriding plate. The width of the proposed flexure depends on the thickness and strength of the South American lithosphere. Such properties probably were not influenced by thermal effects or tectonic discontinuities associated with passive-margin rifting, as this occurred 70–80 m.y. previously. The lithosphere below the passive margin probably was wedge-shaped, thickening landward. Thus, the flexural rigidity increased southward from the continent-ocean boundary, and the width of the forebulge probably increased with time as it migrated. A range of conceivable widths of the forebulge based on theory is 50 to 350 km (inflection to inflection) (Speed and Sleep, 1982).

The locus of first development of the forebulge depends on the locus of the plate edge and vertical loading. It will develop a distance landward of the

plate edge, which is 0.75λ , where λ is the full wavelength of the flexure. Such distance was probably between 70 and 500 km. The plate edge almost certainly occurred in oceanic lithosphere north of the continent. Thus, the locus of the initial forebulge may have been just north of the restored Tinajitas–Peñas Blancas belt, at one limit, or far north of it at the other limit. The distance of forebulge migration was at least 100 km, according to the restoration of facies belts (Figure 4) and width of the belt of unconformity (Figure 5). This distance gives the minimum closure between plates at the convergent boundary.

We now consider the constraints on the subduction zone postulated to exist somewhere off the northern edge of the Eocene South American continent. Because the Eocene unconformity occurs along the full strike length of eastern Venezuela and because it and the migrating ridge are margin-parallel, the subduction zone must have paralleled the continent-ocean boundary. Furthermore, it must have extended eastward at least as far as the northeastern corner of continental South America east of Trinidad (Figure 11).

Such subduction cannot be explained by Caribbean–South American plate interactions. One reason is that reconstructions place the leading edge of the Caribbean plates to the west at least as far as Central America in the Eocene (Sykes et al., 1982; Pindell and Barrett, 1990). The Caribbean plate leading edge did not arrive at the longitude of Caracas until almost the Neogene. A second reason is that the Eocene closure required simultaneous north-south convergence, not migrating oblique convergence as existed with the Caribbean–South American plate.

We suggest that north-south plate convergence between the North and South American plates was taken up in the Eocene over a long east-west break in proto-Caribbean (Atlantic) oceanic lithosphere near

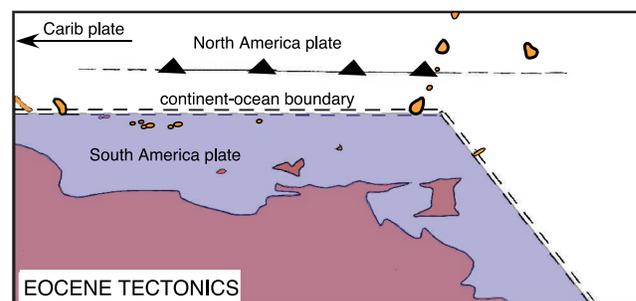


Figure 11. Interpretation of Eocene tectonic setting that produced a migrating flexural bulge (see text).

the continent-ocean boundary (Figure 11). Northward subduction of old oceanic lithosphere of the South American plate caused the Eocene forebulge and unconformity to develop and migrate southward across the margin of that plate. The postulated convergence was short-lived and ceased in the Paleogene. The feasibility of this hypothesis is indicated by Müller et al. (1999, table 10), who identified a discrete phase of 91-km closure between North and South American plates in Eocene time by analysis of new and old Central Atlantic data on isochron ages and fracture zone trends. Our hypothesis assumes that such closure was consumed totally at a proposed subduction locus near the northern margin of the South American continent. If such plate tectonics are valid, we infer, according to the rationale given above, that the initial position of the forebulge was just seaward of the Tinajitas–Peñas Blancas belt.

CONCLUSIONS

In recent years, a number of tectonic models have been proposed to account for changes in sediment accommodation space resulting in expressions of depositional topography and/or relative sea-level change (e.g., Cloetingh et al., 1985, 1989; Heller et al., 1993; Peper, 1994). These models have been applied to both passive-margin and intracratonic basin settings. They have appealed largely to the combination of thermal evolution of lithosphere, loading of lithosphere by sediments, and intraplate stress fields in inhomogeneous lithospheric plates to produce regional tilting and/or flexural features. The scale of these features ranges from meters to more than 100 m in amplitude, from tens of kilometers to >300 km in wavelength, and from <1 m.y. to more than 10 m.y. in duration.

In this study, we investigated the stratigraphy and sedimentology of Paleogene strata in eastern Venezuela that were deposited during the transition from a passive margin to a foreland fold and thrust belt. The succession of lithologies and faunas, elongate geometry of skeletal carbonates, and regional distribution of unconformity landward of the Tinajitas–Peñas Blancas Limestones indicate a major change in bathymetry and sediment accommodation (shift from slope siliciclastics to shoal-water carbonates, and back again). The changes are best explained as consequences of a migrating elastic flexural forebulge. The amplitude of the flexure was at least 800 m, the wavelength from 70 to 500 km, and the duration from 10 to 20 m.y. The cause of the migrating elastic

flexure may have been a pulse of Eocene convergence between the North and South American plates. These findings suggest a significant increase in the scale of tectonic features capable of producing regional unconformity in sedimentary basins.

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