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Late Cretaceous marine transgressions in Ecuador and northern Peru: A refined stratigraphic framework

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Abstract

Study of ammonites and bivalves along selected sections on the Andean margin of northern Peru and Ecuador has made it possible to recognize correlatable marine transgressions and propose a refined stratigraphic framework for the Upper Cretaceous of the region. Six maximum flooding events are recognized: latest Turonian–early Coniacian (major event), late Coniacian–early Santonian, early Campanian, mid Campanian–early late Campanian (major event), early Maastrichtian (major event), and terminal early Maastrichtian. Most of these events can be correlated with global eustatic sea level rises, but their relative manifestations indicate that the Andean margin already was being deformed by the late Cretaceous ‘Peruvian’ tectonic events. The onset of fine-grained clastic sedimentation in the Oriente and East Peruvian basins in the mid Turonian–earliest Coniacian is taken as the first event of the ‘Peruvian’ phase. The Campanian regional transgression in the Peruvian–Ecuadorian forearc zones concealed the ‘Peruvian’ deformational event. The latter caused a paleogeographic upheaval, as indicated by the subsequent development of a NNE-trending forearc basin, which extended from Paita in northwestern Peru to northern Ecuador. In the forearc zones, only short-lived transgressions are recorded in the late Campanian and early Maastrichtian as a result of nearly continuous tectonic activity. This activity culminated with a significant tectonic event in the late Maastrichtian that caused a widespread hiatus.

Keywords: Ammonites; Ecuador; Inoceramids; Late Cretaceous; Peru; Stratigraphy; Transgressions

1. Introduction

The active margin of western South America is marked by the development of the extensive Cretaceous Andean Basin, which encompassed large parts of Ecuador, Peru, and central Bolivia. The late Turonian–Maastrichtian interval is a crucial period marked by the onset of compressional deformation and uplift of the Andean margin, followed by a marine regression in the Andean Basin (Steinmann, 1929; Jaillard et al., 2000).

During Albian–Campanian times, the depocenter of the Andean Basin was located in northern Peru. In this area, the Upper Cretaceous sedimentary successions are richly fossiliferous, and the terminal Cretaceous regional regression occurred later than in other Andean areas. Consequently, the Late Cretaceous marine transgressions in this area are well recorded in the sedimentary succession.

Tectonic activity on the Andean margin began in the Late Cretaceous and caused increasing uplift and erosion, particularly in the forearc and arc zones and in the western backarc areas (present-day coast and Western Cordillera). This may have obscured the global, synchronous eustatic signal, which makes reliable chronostratigraphic correlations across the Andes difficult. Although marine transgressions can be caused by tectonic subsidence, tectonic events do not erase the eustatic signal; rather, the sedimentary fill of the tectonically controlled Andean basins record these eustatic transgressions. To verify the eustatic origin of the transgressions, we discuss their geographical extent and compare them to coeval transgressions recorded in other regions in and around South America.

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Although the stratigraphy of these areas has been studied since early in the last century, no detailed biostratigraphic work has been carried out in the past 50 years. In this article, we review the paleontological data and stratigraphic assignments in the light of current paleontological and biostratigraphic knowledge. However, the nature, evolution, and age range of the South American macrofaunas remain poorly known, which makes accurate determinations and datings difficult. Nevertheless, precise dating of the maximum flooding events of marine transgressions, used as timelines, makes it possible to correlate the forearc and backarc deposits, and thereby the sedimentary and tectonic events across the Andean margin, and ultimately to clarify the early evolution of the Andean margin.

For these reasons, we undertook a detailed stratigraphic study of the Upper Cretaceous of northern Peru and Ecuador. We present our results for the Late Turonian–Maastrichtian succession based on study of macrofossils (mainly ammonites and inoceramid bivalves) collected from sections in eastern and southern Ecuador and northern Peru (Fig. 1). Numbers in brackets after species names are field codes that denote locality or horizon. Species mentioned in the literature without description or illustration or that lack precise locality data are not discussed in detail.

For the Turonian–Coniacian and Campanian–Maastrichtian stage boundaries, we use definitions based on the proposed Global Boundary Stratotype Section and Point (GSSP) for the base of the Coniacian (Kauffman et al., 1996) and the ratified GSSP for the base of the Maastrichtian (Odin and Lamaurelle, 2001). The Coniacian–Santonian and Santonian–Campanian stage boundaries have not yet been formally defined.

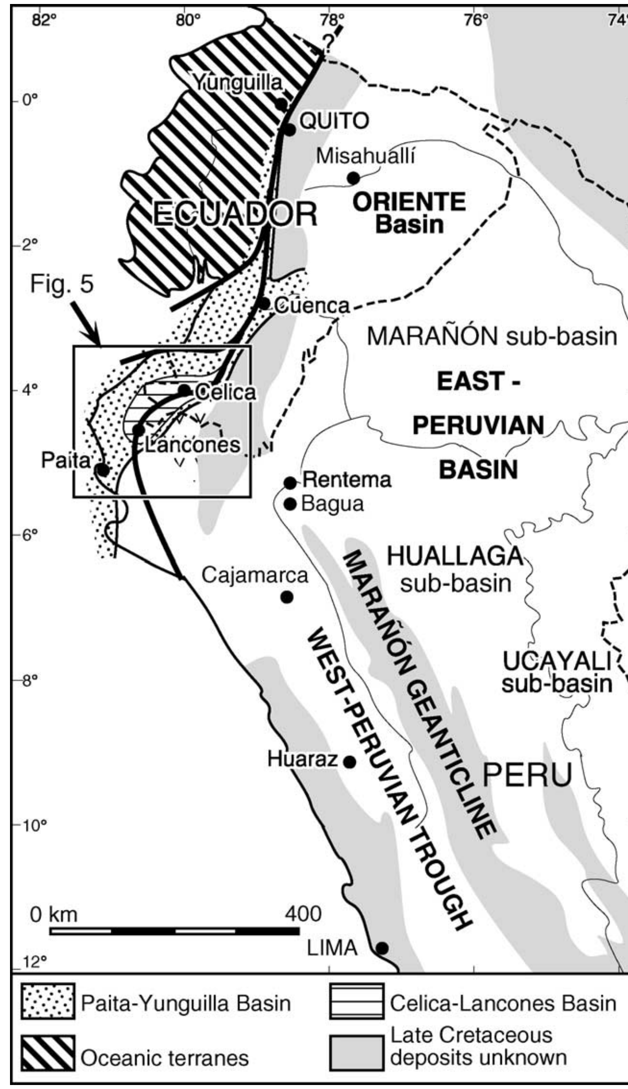

Fig. 1. General location map.

2. Geological setting

During the Cretaceous, the Andean margin was submitted to continuous N- to NE-directed subduction. The Peruvian margin comprised, from west to east, a narrow forearc zone; a poorly known, mainly subaerial arc zone; and a wide backarc zone. The backarc zone comprised a subsiding basin in the west (West Peruvian Trough, Fig. 1), which was separated from a moderately subsiding basin in the east (East Peruvian Basin) by a positive area (Marañón Geanticline, Benavides-Cáceres, 1956; Wilson, 1963). In Ecuador, the eastern backarc zone, represented by the Oriente Basin, is separated from the significantly deformed western areas by the present-day Eastern Cordillera. There, intraoceanic subduction is assumed to have occurred farther west and eventually caused accretion of oceanic terranes in the Late Cretaceous–Paleogene (Reynaud et al., 1999; Kerr et al., 2002).

Recent geological studies and mapping of the forearc zones have shown that the Cretaceous sedimentary rocks belong to two distinct forearc basins of early Late Cretaceous and latest Cretaceous age, respectively (Jaillard et al., 1996, 1998, 1999). The deposits contained in these basins are separated by a regional unconformity (Jaillard et al., 1999) related to the ‘Peruvian’ tectonic phase (Steinmann, 1929). Most of the data presented here relate to the La Tortuga and La Mesa sections, south of Paita in northwestern Peru, and to the ‘Celica–Lancones Basin.’ The latter comprises an eastern arc succession (río Playas) and a western succession that constitutes the cover of the Amotape–Tahuin massif (Puyango–Cazaderos) (Figs. 1 and 4). In addition, biostratigraphically significant macrofossils have been collected from numerous outcrops in northwestern Peru and southern Ecuador.

The West Peruvian Trough, which received a thick pile of mainly marine sediments between Valanginian and Campanian times (Benavides-Cáceres, 1956; Robert, 2002), comprises a strongly subsided zone centered around Huaraz and a moderately subsided platform north of Cajamarca (Fig. 1). The Trough does not extend northward into Ecuador. The sections studied are located at Cajamarca and Pongo de Rentema; the latter is situated on the boundary between the West Peruvian Trough and the East Peruvian Basin (Bagua Basin of Mourier et al., 1988).

The eastern basins of Ecuador (Oriente) and Peru (Marañón, Fig. 1) are characterized by marine deposits of Albian–Santonian age, followed by a dominantly nonmarine succession of Maastrichtian–Eocene age (Tschopp, 1953; Mathalone and Montoya, 1995; Jaillard, 1997a). Data from these areas are based on the Río Misahuallí (Ecuador) and Pongo de Rentema (Peru) sections, scattered outcrops, and published and unpublished data related to petroleum exploration.

The forearc basins are characterized by active tectonics, subsiding and mobile troughs, and open marine environments that continued locally until the end of the Eocene. In contrast, the eastern basins are marked by stable tectonic conditions, low subsidence rates, shallow restricted environments, and short-lived (though widespread) marine transgressions during the Santonian–Maastrichtian. The West Peruvian Trough displays intermediate characteristics. Therefore, a biostratigraphic correlation of the fossiliferous, open marine assemblages of the forearc zones with the restricted, mainly micropaleontological assemblages of the eastern basins presents some problems.

3. Post-Turonian transgressions in the backarc basins

The Turonian of the Andean Basin was characterized by sedimentation on a wide carbonate platform. This depositional regime was interrupted during the late Turonian–early Coniacian by a major transgression that marked the onset of extensive fine-grained terrigenous clastic sedimentation (Benavides-Cáceres, 1956; Wilson, 1963; Jaillard, 1994).

3.1. Latest Turonian–early Coniacian maximum flooding event

3.1.1. Peru

From the marls of the Chonta Formation of the northern part of the East Peruvian Basin (Marañón Basin, Fig. 1), Kummel (1948), Rosenzweig (1953), and Ducloz and Rivera (1956) reported numerous specimens of the ammonite genus *Tissotia*, some *Lenticeras*, *Buchiceras*, *Barroisiceras*, and scarce *Coilopoceras*, *Eulophoceras*, and *Vascoceras*. They considered this fauna of Turonian(?)–Coniacian age. Zegarra (1964) mentioned a fauna characterized by *Barroisiceras* sp. (including *B*. cf. *haberfellneri* [von Hauer, 1866]) and *Buchiceras bilobatum* Hyatt, 1875, associated with *Hauericeras* sp., *Peroniceras* cf. *moureti* de Grossouvre, 1894, *Lenticeras andii* (Gabb, 1877), desmoceratids, and tissotiids.

In the northern part of the West Peruvian Trough (Cajamarca area), Benavides-Cáceres (1956) defined the *Buchiceras bilobatum* Zone as containing species of *Barroisiceras*, *Solgerites*, *Forresteria*, *Tissotia*, *Heterotissotia*, and *Buchiceras*, traditionally a typical lower Coniacian assemblage (Bengtson, 1988). However, the recently proposed GSSP for the base of the Coniacian (base of bed MK 47 in the Salzgitter–Salder quarry in Lower Saxony, Germany; Kauffman et al., 1996) lies stratigraphically higher than the previously accepted stage boundary, which was based on ammonites. The *Buchiceras bilobatum* Zone, at least in part, should therefore be referred to the upper Turonian.

Extensive collections along the Pongo de Rentema section, on the boundary between the West and East Peruvian basins (Figs. 1 and 2), have yielded the following ammonites and bivalves in situ, listed in stratigraphical order:

- From Turonian marls and limestones: Coilopoceratidae sp. (R.69), *Mytiloides labiatus* (von Schlotheim, 1813) (R.69), and *Kamerunoceras*? sp. (R.70); and
- From Coniacian shales: *Paratissotia* sp. (R.77), *Texanites* cf. *vanhoepeni* Klinger and Kennedy, 1980 (R.77), *Heterotissotia* juv. (R.145), *Lenticeras* sp. (R.146), *Metatissotia*? sp. (R.152, R.121, R.124), *Lenticeras andii* (R.152), and Tissotiidae indet. (R.128, R.130, R.131). The bivalves *Platyceramus* cf. *cycloides* (Tschopp, 1953) (R.152), *Platyceramus* sp. (96.R.156), and *Cordiceramus* ex. gr. *muelleri* (Petrascheck, 1904) (R.156) in the lower part of the succession and *Platyceramus cycloides* (R.124) in the upper part suggest a Coniacian–Santonian age (Fig. 2).

In addition to these specimens, we have studied material collected by geologists of Petróleos del Perú (PetroPerú) S.A. and Occidental Petroleum Company (Oxy) from the Pongo de Rentema section. This material has been calibrated with our data, though many of the PetroPerú and Oxy specimens appear derived from higher levels as a result of gravitational and/or river transport.

The late Turonian–early Coniacian transgression is associated with the onset of terrigenous clastic deposition.

3.1.2. Ecuador

From the Oriente Basin (Fig. 3), Tschopp (1953) and Hobbs (1975) reported *Peroniceras* sp. (lower or middle Coniacian). In the northern part of the basin (Río Quijos), Monciardini et al. (1984) ascribed a 10 m thick succession to the Coniacian on the basis of the foraminifers *Archeoglobigerina* aff. *cretacea* (d'Orbigny, 1840), *Dicarinella primitiva* (Dalbiez, 1955), and *Marginotruncana* ex gr. *renzi-angusticarinata* (Gandolfi, 1942).

A latest Turonian (in current terms) marine transgression has also been identified in the río Misahuallí section (Jaillard, 1997a, Fig. 3). At the top of the upper Turonian M-2 limestones, transgressive calcareous beds yielded the inoceramid *Mytiloides* sp. and the ammonite *Barroisiceras* sp. (95.5). From a level 10 m above these occurrences, in marine shales representing the maximum flooding event, we collected *Mytiloides* sp. (94.39, 94.39a), *Archeoglobigerina* aff. *cretacea*, *Dicarinella primitiva*, and *Hedbergella planispira* (Tappan, 1940) and the nannofossil *Marthasterites furcatus* (Deflandre in

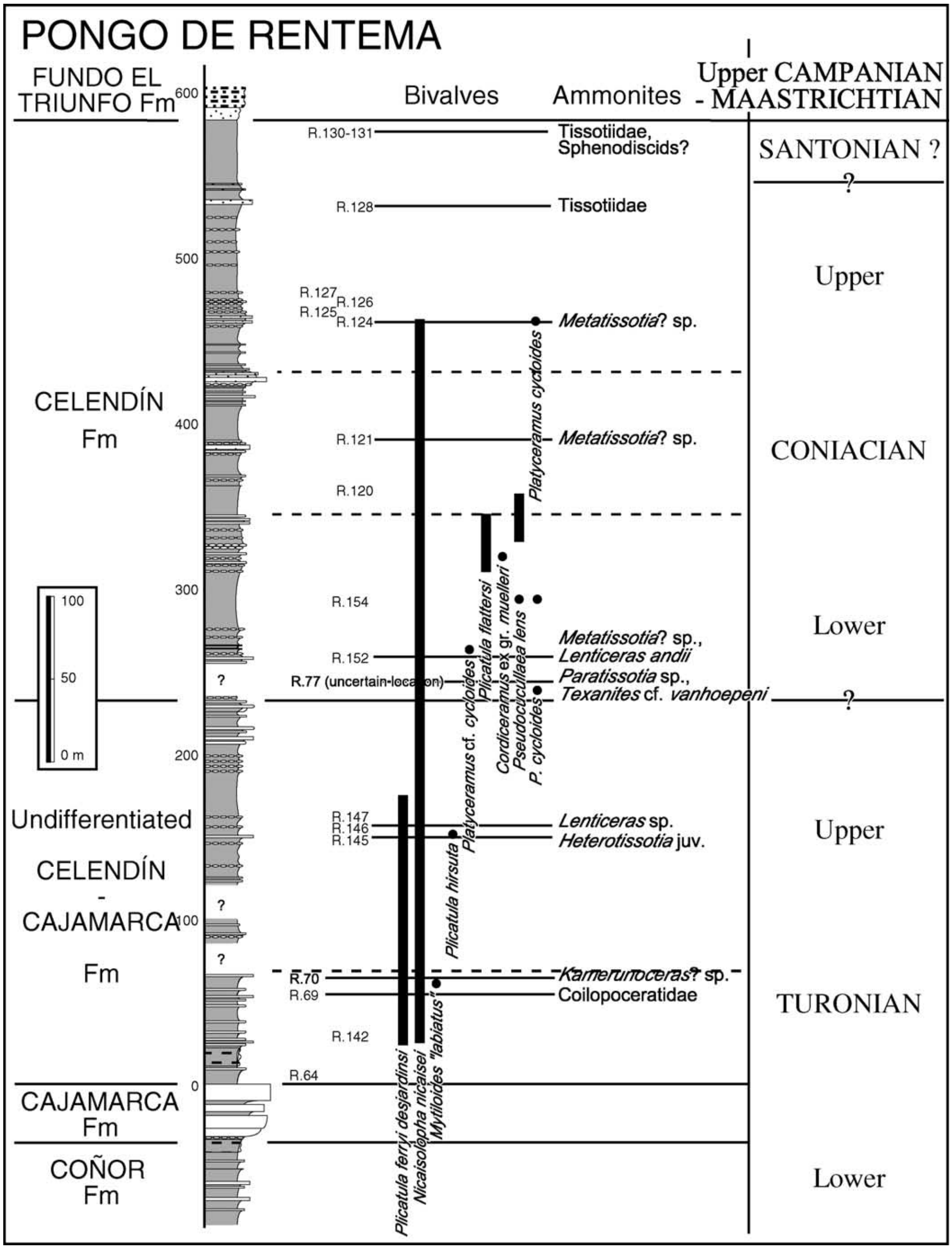

Fig. 2. Stratigraphic section at Pongo de Rentema (northern Peru) with ranges and occurrences of the main diagnostic taxa.

Deflandre and Fert, 1954) (Jaillard, 1997a). The cooccurrence of *Mytiloides* sp. and *Barroisiceras* in this section indicates a latest Turonian age for the transgression, consistent with the occurrence of *Dicarinella* ex gr. *hagniconcavata* (Brotzen, 1934), *Marginotruncana sigali* (Reichel, 1949), and *Whiteinella* spp. in the transgressive beds disconformably overlying the M-2 limestones in the Mirador section (Jaillard, 1997a).

Farther north (Río Quijos), from shales approximately 20 m above the M-2 limestones, P. Baby (IRD) collected a loose impression of a peroniceratine ammonite (96.13Eb), suggesting an early or mid Coniacian age.

3.2. Late Coniacian–early Santonian maximum flooding event

3.2.1. Peru

In the East Peruvian Basin of northern Peru, Kummel (1948), Rosenzweig (1953), and Ducloz and Rivera (1956) found no evidence of the Santonian. Zegarra (1964) mentioned the ammonite *Texanites* sp. and numerous specimens of *Tissotia* (*T.* cf. *singewaldi* Knechtel, 1947, *T.* cf. *roscheni* Knechtel, 1947, *Tissotia* nov. sp.) collected above the *Barroisiceras–Buchiceras* assemblage, indicating the middle or upper Coniacian.

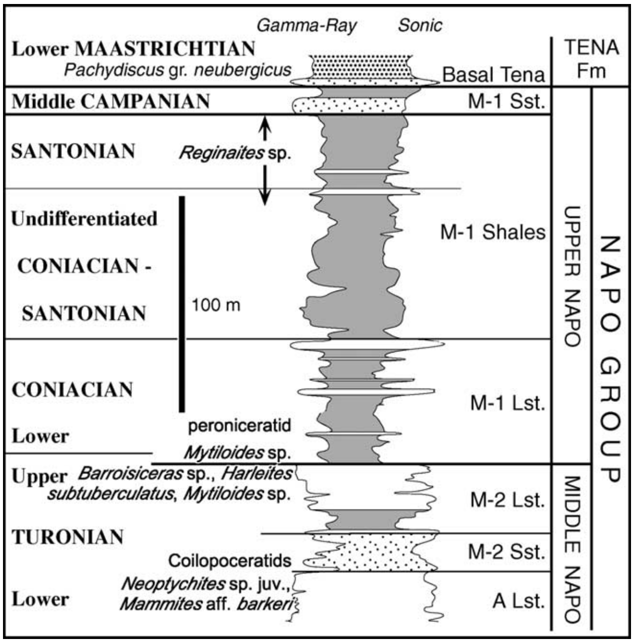

Fig. 3. Section and electric logs for the Oriente Basin (Ecuador), with stratigraphic occurrences of the main diagnostic taxa.

In the northern part of the West Peruvian Trough (Cajamarca area), Benavides-Cáceres (1956) defined the *Lenticeras baltai* Zone and described *Bostrychoceras*? sp., -*Desmophyllites gaudana* (Forbes, 1846), *Texanites hourcqi* Collignon, 1948, *Tissotia steinmanni* Lisson, 1908, *T. fourneli* (Bayle, 1850), *T. halli* Knechtel, 1947, and *Lenticeras lissoni* (Knechtel, 1947). He considered this assemblage broadly Santonian in age, later referred by Bengtson (1988) to probably the early Santonian. However, ammonite systematics and international chronostratigraphic correlations around the Coniacian–Santonian boundary remain imprecise, and even a late Coniacian age must be considered possible, especially because the genus *Tissotia* is not definitely known from post-Coniacian levels (Wright, 1996).

A late Coniacian–early Santonian age for the middle part of the Celendín Formation *s.s* is supported by the appearance of the bivalves *Platyceramus cycloides* (R.124) of Santonian–early Maastrichtian age and *Cordiceramus* ex gr. *muelleri* (Fig. 2).

3.2.2. Ecuador

From the southern part of the Oriente Basin (Fig. 3), Hobbs (1975) mentioned a tissotiid ammonite. In the northern part of the basin (Río Quijos), Monciardini et al. (1984) determined a Santonian foraminiferal association with *Dicarinella concavata* (Brotzen, 1934) (aff. *asymetrica* [Sigal, 1952]), *D.* cf. *ventricosa* (White, 1928), and several species of *Marginotruncana* in a 20 m thick succession. In addition, detailed micropaleontological studies (mainly of palynomorphs) have indicated a Santonian age for the upper part of the upper Napo Formation (e.g. Robertson Research, 1988; see review in Jaillard, 1997a).

In southeastern Ecuador (Santiago–Morona Road), an isolated outcrop of marls and limestones (94.76) yielded a *Reginaites* sp. (Santonian–lower Campanian; Klinger and Kennedy, 1980; Wright, 1996) associated with *Plicatula ferryi* Coquand, 1862, *Pycnodonte flicki* Pervinquière, 1912, and Coniacian–Santonian echinoids; taken together, these suggest a Santonian age. Although well-exposed field sections are lacking, the occurrence of these species and the micropaleontological data collected from wells (see Jaillard, 1997a) suggest that the late Coniacian–early Santonian transgression reached part of the Oriente Basin.

3.3. Late Santonian–early Campanian maximum flooding event

In the Pongo de Rentema section (Fig. 2), we found no ammonites of Santonian or younger age in situ, though the highest levels exposed of the Celendín Formation yielded fragments of smooth, flat sphenodiscids (R.130, R.131; Fig. 2) together with 'untypical' tissotiids, which seems to indicate a faunal change. A *Submortoniceras* sp. (349) collected by PetroPerú geologists from 5 m above their last tissotiid specimen but some 30 m below our definite last occurrence of this taxon (R.128) may derive from stratigraphically higher beds exposed in the vicinity. Similarly, a sphenodiscid (13) collected by Oxy geologists from near the top of the marine sequence may have come from higher levels.

In the Oriente Basin of Ecuador, the upper part of the M-1 shales (upper Napo Formation, Fig. 3) locally comprises marine shelf shales and fine-grained sandstones as a distinct sedimentary body (Rivadeneira et al., 1995). In the central part of the basin, this unit yields an association of palynomorphs, dinocysts, and a few nannofossils, which indicate a late Santonian–earliest Campanian age (Raynaud et al., 1993; Robertson Research, 1997). Because these beds are separated from the over- and underlying beds by unconformities (Raynaud et al., 1993; Robertson Research, 1997), they probably represent transgressive to maximum flooding deposits. However, because the contact with the overlying sandstones is erosional, the deposits are only known locally.

3.4. Mid to early late Campanian maximum flooding event

In the eastern basins, massive transgressive sandstones (lower Vivian Formation of the Marañón Basin, M-1 sandstones of Ecuador, Fig. 3) are overlain by a thin layer of marine shales with palynomorphs that suggest the middle part of the Campanian (in Peru: Salas, 1991; Mathalone and Montoya, 1995; in Ecuador: Mills, 1972; Robertson Research, 1988, 1997; Raynaud et al., 1993; also see review in Jaillard, 1997a).

This transgression is well manifested in the Bagua area of northern Peru (Mourier et al., 1988), where the upper levels of the Celendín Formation contain the ammonites *Manambolites* sp. and *Libycoceras* sp. (abundant), associated with *Menabites* sp., *Submortoniceras* sp., and *Pachydiscus* sp.

juv. (Bengtson, 1988), the latter now reassigned to *Menuites* sp. Collecting by J. Jacay (University of San Marcos, Lima) in the Bagua Basin in 1994 yielded a very similar fauna from Gallo Cantana, approximately 20 km south of Bagua (Fig. 1).

3.5. Early Maastrichtian maximum flooding event

In the eastern basins of Peru and Ecuador, thin marine layers that represent an early Maastrichtian transgression have been recognized. From the Cachiyacu Formation of Peru (Fig. 10), a *Sphenodiscus* sp. (Rodriguez and Chalco, 1975), an unidentifiable ammonite (Vargas, 1988), and early Maastrichtian microfossils (Gutierrez, 1975; Müller and Aliaga, 1981) have been reported. This unit traditionally is referred to the early Maastrichtian (Kummel, 1948; Salas, 1991; Mathalone and Montoya, 1995). Marine deposits of comparable lithology and faunal content have been described from the East Peruvian Basin of central (Koch and Blissenbach, 1962; Robertson Research, 1990) and southern (Dávila and Ponce de León, 1971; Soto, 1982) Peru, as well as from the Altiplano of southern Peru (Jaillard et al., 1993) and Bolivia (Sempéré et al., 1997).

The Tena Formation of the Oriente Basin (Ecuador, Figs. 3 and 10) locally yielded the planktonic foraminifers *Globotruncana* cf. *lapparenti* Brotzen, 1936, *Rugoglobigerina* cf. *rugosa* (Plummer, 1926) (Sigal, 1969; Mills, 1972; Bristow and Hoffstetter, 1977), *Globotruncana aegyptica* Nakkady, 1950, and *G. plummerae* (Gandolfi, 1955) (Whittaker and Hodgkinson, 1979), which suggest the upper part of the lower Maastrichtian. More recently, detailed studies of pollen and dinoflagellates have led Raynaud et al. (1993) to ascribe the basal part of the Tena Formation (Basal Tena unit) to the lower Maastrichtian.

Finally, along the Santiago-Morona Road in southern Ecuador (8.3 km east of Río Yaupi), we collected two ammonites from the base of the Tena Formation, identified as *Pachydiscus* ex gr. *neubergicus* of early Maastrichtian age.

Marine bivalves and unidentifiable large ammonites have been reported from shelf deposits of the southern part of the sub–Andean zone of Ecuador ('Limón Flysch'), dated by Maastrichtian foraminifers (Faucher et al., 1971; Bristow and Hoffstetter, 1977). These beds may have been deposited in an embayment of the forearc zone connected to the eastern Oriente Basin. Thus, the early Maastrichtian maximum flooding event appears to have been a major marine transgression in the eastern part of the Andean Basin.

4. Post-Turonian transgressions in the forearc basins

The stratigraphy of the forearc zones of northern Peru and southern Ecuador has been studied by Sigal (1969), Kennerley (1973), and Bristow and Hoffstetter (1977) in southwestern Ecuador and by Iddings and Olsson (1928), Olsson (1934, 1944), Fisher (1956), Reyes and Caldas 1987), and Reyes and Vergara (1987) in northwestern Peru. The forearc zone comprises two successive sedimentary basins of Cretaceous age separated by a regional unconformity related to the 'Peruvian' tectonic phase (Jaillard et al., 1996; 1999).

The 'Celica–Lancones Basin' is a tectonically active Albian–Coniacian trough infilled mainly by turbidites and located in northwestern Peru and southwestern Ecuador between a volcanic arc to the east and southeast and the Paleozoic Amotape-Tahuin massif to the west and northwest (Fig. 4). Therefore, the western succession constitutes the sedimentary cover of the Amotape-Tahuin Massif, whereas the eastern succession comprises volcanic arc rocks and related volcaniclastic sediments of probably Albian age.

The sediments of the 'Celica–Lancones Basin' are disconformably overlain by the NNE-trending 'Paita-Yunguilla forearc basin' (formerly included in the 'Celica–Lancones Basin'), the Campanian–Maastrichtian sediments of which onlap onto the western Amotape-Tahuin massif and the eastern volcanic arc. The basin extends into northern Peru to the south and western Ecuador to the north. Its Campanian transgressive sediments rest disconformably on Paleozoic rocks (Paita area), deformed Albian and Upper Cretaceous rocks ('Celica–Lancones Basin'), and deformed, accreted oceanic rocks of Cretaceous age (Western Cordillera of Ecuador). It is therefore likely that the tectonic activity disturbed the eustatic signal in these areas.

4.1. Latest Turonian–Coniacian maximum flooding events

The youngest fossils previously reported from the 'Celica–Lancones Basin' are the latest Turonian ammonites cf. *Barroisiceras haberfellneri* (Petersen, 1949) and *Barroisiceras* sp. (Reyes and Vergara, 1987) and a 'Senonian' microfauna (Weiss, 1955) found in drill holes but without a precise stratigraphic location. Near Angolo in northern Peru, we collected a loose impression of *Protexanites* cf. *cycni* (van Hoepen, 1965) (00.A.4Eb), a species referred to the early Coniacian by Klinger and Kennedy (1980). These faunas apparently belong to the latest Turonian–early Coniacian transgression in this turbiditic trough.

Santonian deposits appear absent, probably as a result of deformation and erosion related to the 'Peruvian' tectonic phase, which separates the evolution of the 'Celica–Lancones' and 'Paita-Yunguilla' basins (Fig. 5).

4.2. Late Santonian–early Campanian maximum flooding event

In the 'Celica–Lancones Basin' east of the Celica area (río Playas section), volcanic and volcaniclastic rocks of the Albian(?) magmatic arc are unconformably overlain by marine marls, shales, and sandstones of the El Naranjo Formation (Fig. 5). The basal transgressive part of these beds yielded *Plesiotexanites (Eutexanites) sextuberculatus* Klinger and Kennedy, 1980 (PO.114) and *Submortoniceras* sp. (96.1), which suggest an early Campanian age (Fig. 5). Associated bivalves (*Trigonarca* sp., *Panopea* sp.,

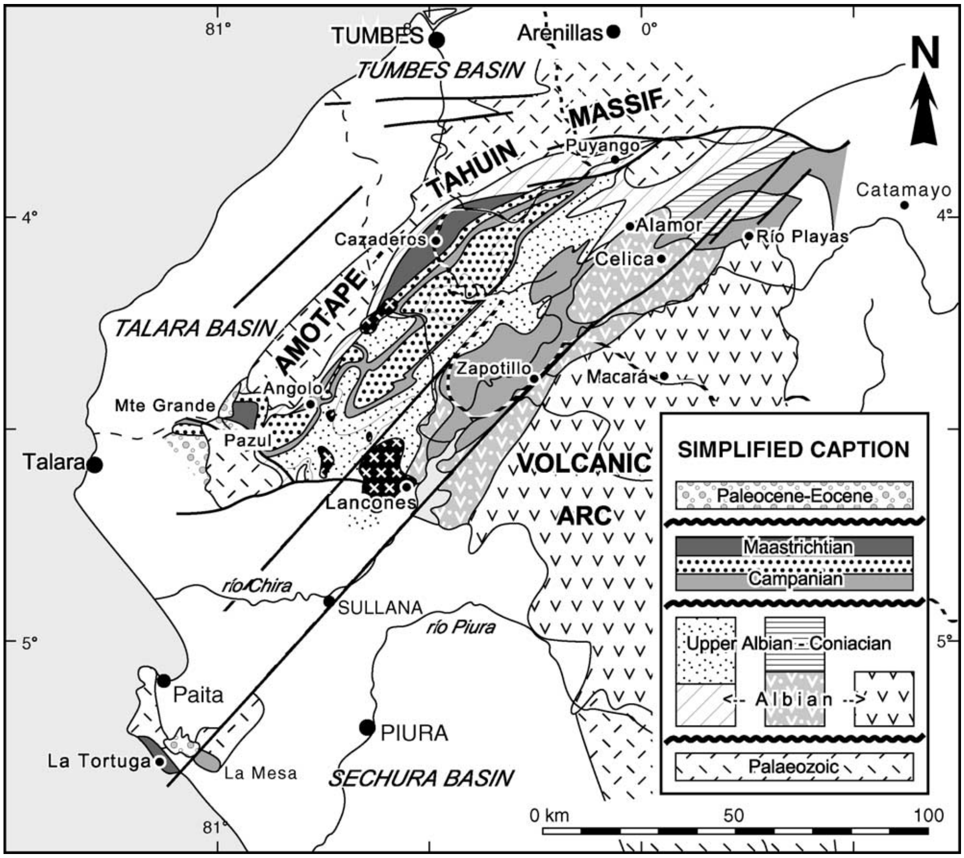

Fig. 4. Geological sketch map of the Paita and Celica–Lancones areas with location of the main sections and localities cited in the text (Talara, Tumbes, and Sechura basins are Tertiary).

Pseudocucullaea lens Solger, 1903) and a few diagnostic nanofossils (*Micula decussata* Vekshina, 1959, *Quadrum gartneri* Prins and Perch-Nielsen, 1977) are consistent with this age (Jaillard et al., 1996; Pérez and Reyes, 1996; Bengtson and Jaillard, 1997). Because these early Campanian marine beds are only recorded in this area, a tectonic origin for this localized transgression is probable.

4.3. Mid–late Campanian transgression

4.3.1. Paita area

The La Mesa section, southeast of Paita (Fig. 4), comprises three lithologic units (Fig. 6). The lower unit consists of transgressive shales, sandstones, and limestones with ammonites of the genus *Coahuilites* (95.LM.7), which indicate an age not older than late Campanian. The bivalves *Ambigostrea villei* (Coquand, 1862) (95.LM.1, 95.LM.5, 95.LM.6, 95.LM.26, 95.LT.4, 97.17) and *Plicatula harrisiana* Olsson, 1934 (95.LM.5, 97.17) indicate the Campanian–Maastrichtian interval.

The middle unit is represented by massive rudist-(radiolitids) and gastropod-bearing shelf limestones that lack diagnostic faunas.

The upper unit consists of marls intercalated with limestone and sandstone beds, the lower part of which yielded *Nostoceras* sp. (95.LM.26) and *Libycoceras* sp. (95.LM.26), as well as other sphenodiscid ammonites. The genus *Nostoceras* indicates a late Campanian age, as supported by the associated bivalve fauna (e.g. *Plicatula harrisiana* [97.17], *Cataceramus* aff. *goldfussianus* [97.17, 97.19Eb, PO.467], and rudists belonging to the genera *Biradiolite*s, *Radiolites*, and *Praebarretia*) (Fig. 6).

4.3.2. Celica–Lancones area

In the Río Playas section, the fine-grained marls of the upper El Naranjo Formation reflect a new widespread marine transgression (Fig. 5). These beds yielded the ammonites *Menuites* sp. (PO.19) and *Exiteloceras*? sp. (PO.19, PO.98) of Campanian age, associated with the Santonian–early Maastrichtian *Platyceramus* cf. *cycloides* (PO.261) and microfossil assemblages (radiolarians, foraminifers, nanofossils) of late Campanian–Maastrichtian age (Jaillard et al., 1996, 1999).

In the central (Zapotillo, Lancones) and western (Angolo) parts of the Celica–Lancones area, the early Late Cretaceous turbidites are overlain unconformably by black shales with limestone nodules and arkosic beds (Zapotillo Formation of Ecuador, Angolo Formation of Peru). These yielded a pachydiscid ammonite (00.A.05Eb) and *Submortoniceras* sp. (96.4, 96.5, 97.Ce.45), which indicate an

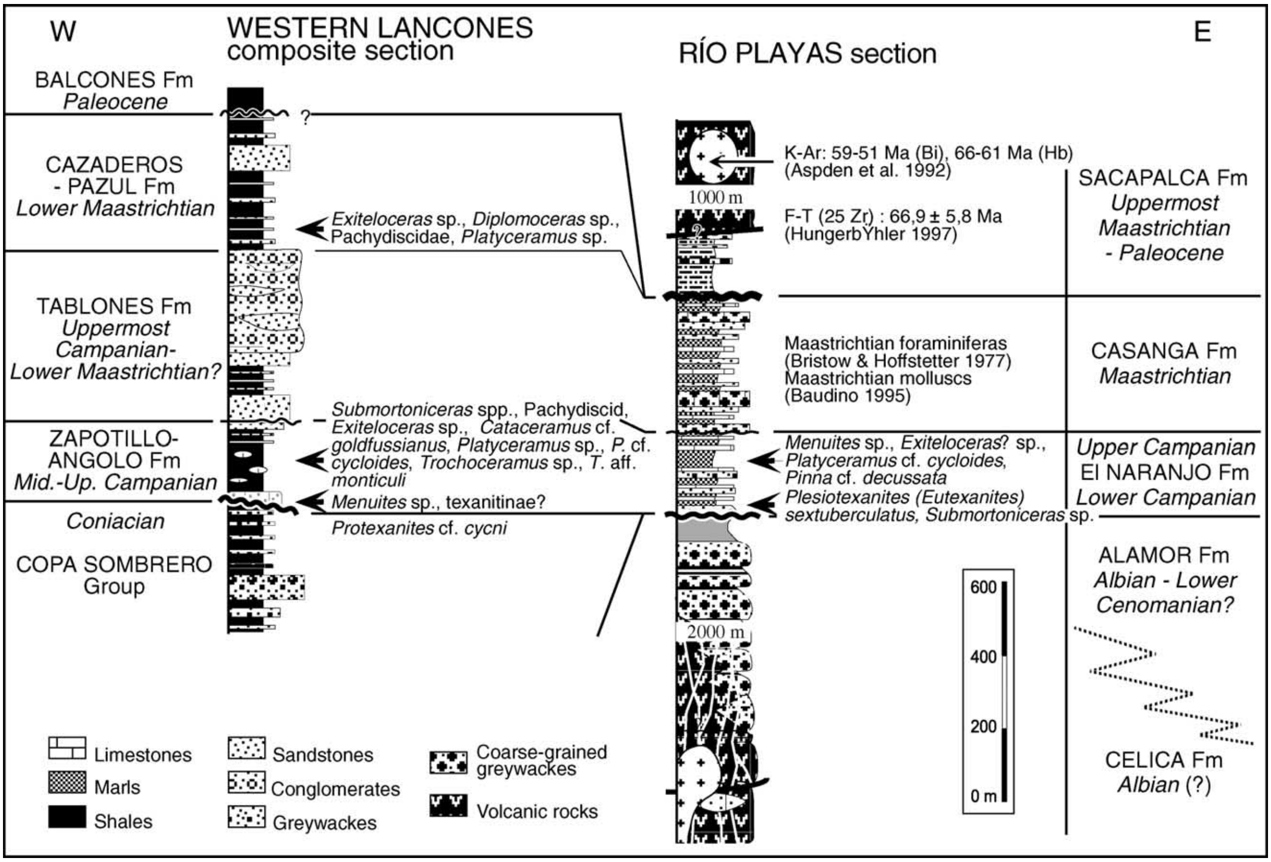

Fig. 5. Sections in the western (Puyango–Cazaderos) and eastern (Río Playas) parts of the 'Celica–Lancones Basin,' southern Ecuador (Fig. 4), with location of the main diagnostic taxa.

age between late Santonian and mid Campanian. At Puyango (Ecuador), transgressive limestones resting on deformed Albian limestones yielded a poorly preserved texanitinae? (95.30), and a *Menuites* sp. (PO.464Eb) collected loose. In the Monte Grande area in Peru, in a fault-bounded outcrop of shales ascribed to the Angolo Formation, we collected *Exiteloceras* sp. (95.MG.2) of Campanian age.

In the entire area, the Zapotillo and Angolo formations are characterized by the large inoceramid *Platyceramus* sp. (96.4, 97.19, 97.20, 99.A.19Eb, 99.A.20Eb, 99.A.22Eb, 00.A.08Eb, 00.A.18, 00.A.19, 00.A.20) and *P.* cf. *cycloides* (96.X) of Santonian–early Maastrichtian age, associated with scarcer *Trochoceramus* sp. (97.20) (latest Campanian–mid Maastrichtian), *Trochoceramus* aff. *monticuli* (Fugger and Kastner, 1885) (96.X) (latest Campanian–early Maastrichtian), and *Cataceramus* cf. *goldfussianus* (d'Orbigny, 1847) (97.19Eb) (late Campanian). As a whole, this assemblage suggests a mid-late Campanian age (Fig. 5).

4.3.3. Western Ecuador

In the Western Cordillera of central Ecuador, the Maastrichtian Yunguilla 'Flysch' locally contains interbeds of calciturbidites (San Juan limestones) dated as Campanian–early Maastrichtian (Thalmann, 1946; Kehrer and Kehrer, 1969). Part of the Yunguilla Formation may be coeval with the mid–late Campanian transgression.

4.4. Early–mid Maastrichtian transgressions

4.4.1. Paita area

The La Tortuga section, south of Paita (Fig. 4), comprises two formations. The La Tortuga Formation consists of approximately 4000 m of red breccias, which include a shaly interval that represents a marine transgression (La Tortuga beds of Olsson, 1944; middle unit in Fig. 7). Farther northwest, the Cenizo Formation consists of disconformable, coarse-grained sandstones and subordinate conglomerates that rest directly on Paleozoic rocks.

The middle unit of the La Tortuga Formation yielded *Sphenodiscus* sp. (00.LT.9) and numerous bivalves ascribed to the Campanian–Maastrichtian boundary interval (Fig. 7).

The La Tortuga upper breccias are capped by transgressive, fossiliferous yellow sandstones (Baculites sandstones of Olsson, 1944; lower Cenizo Formation in Figs. 7 and 8), which yielded numerous *Eubaculites* cf. *carinatus* (Morton, 1834) (95.LT.2) and one *Hypophylloceras (Neophylloceras) surya* (Forbes, 1846) (95.LT.2) of Maastrichtian age (Bengtson and Jaillard, 1997), probably early Maastrichtian (cf. Courville and Odin, 2001). Associated with these

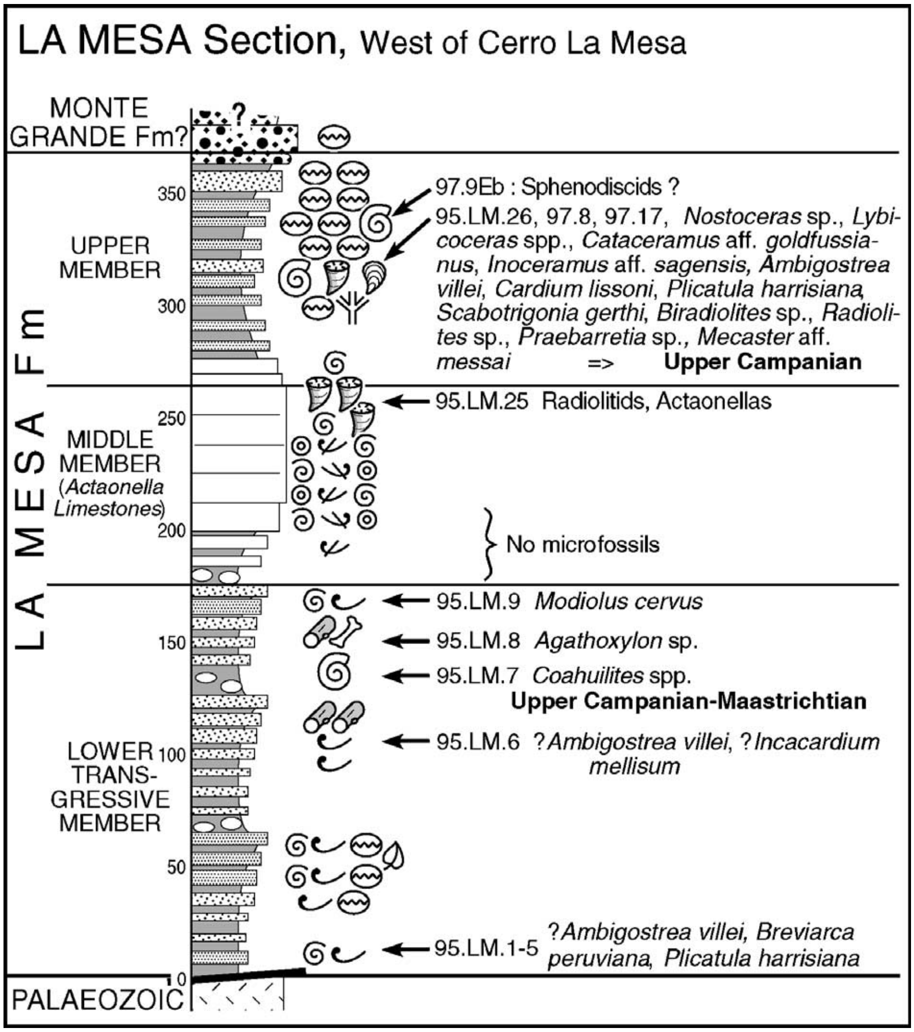

Fig. 6. Section of the La Mesa Formation in the Paita area of northwestern Peru with location of diagnostic taxa.

ammonites are numerous well-preserved bivalves, among which *Trochoceramus* cf. *nahorianensis* Kociubynskij, 1968 (95.LT.2) indicates a late Campanian–early Maastrichtian age (Dhondt and Jaillard, 2006). Sample 00.LT.4 from the same unit might be either *Inoceramus sagensis* Owen, 1852, of Campanian age or, more probably, a *Trochoceramus* sp., which indicates a pre-late Maastrichtian age (Walaszczyk et al., 2001, 2002a,b).

The upper part of the Cenizo Formation (Radiolites sandstones of Olsson, 1944) overlies dark-colored conglomerates. Its lower part yielded *Pachydiscus* cf. *epiplectus* (Redtenbacher, 1873) (99.SC.3), *P. dossantosi* (Maury, 1930) (99.SC.9Eb), and *Eubaculites* sp. (00.LT.3), suggesting an early Maastrichtian age. Bivalves include the inoceramid *Trochoceramus*? sp. and numerous rudists of the genus *Macgillavryia*. The middle part of the Cenizo Formation thus seems to be early Maastrichtian in age (Fig. 8).

According to these data, the older transgression (middle La Tortuga Formation) can be dated as late Campanian and the succeding ones (lower and middle Cenizo Formation) as early Maastrichtian.

4.4.2. Celica–Lancones area

The Campanian Zapotillo and Angolo formations are overlain by thick, coarse-grained conglomerates (Tablones Formation), which in turn are overlain by shales with limestone nodules and intercalations of quartz-rich, medium-grained turbidites (Cazaderos Formation in Ecuador, Pazul Formation in Peru, Fig. 5). In the western part of the area, these beds locally cover the Albian transgressive beds directly.

In the Cazaderos area (Ecuador), the Cazaderos Formation yielded *Diplomoceras* sp. (95.33, PO.482), *Exiteloceras* sp. (PO.482), and an unidentifiable large pachydiscid (95.40Eb) collected loose. In the same area, we collected *Platyceramus* sp. (PO.482, 99.A.11Eb) of Coniacian–early Maastrichtian age. This fauna and the stratigraphic relationships are consistent with a late Campanian–early Maastrichtian age.

4.4.3. Western Ecuador

In the Western Cordillera of central Ecuador (Fig. 1), the shales and turbidites of the Yunguilla Formation *s.s.* are dated with foraminifers as Maastrichtian (Thalmann, 1946; Sigal, 1969; Bristow and Hoffstetter, 1977; Pratt et al., 1998).

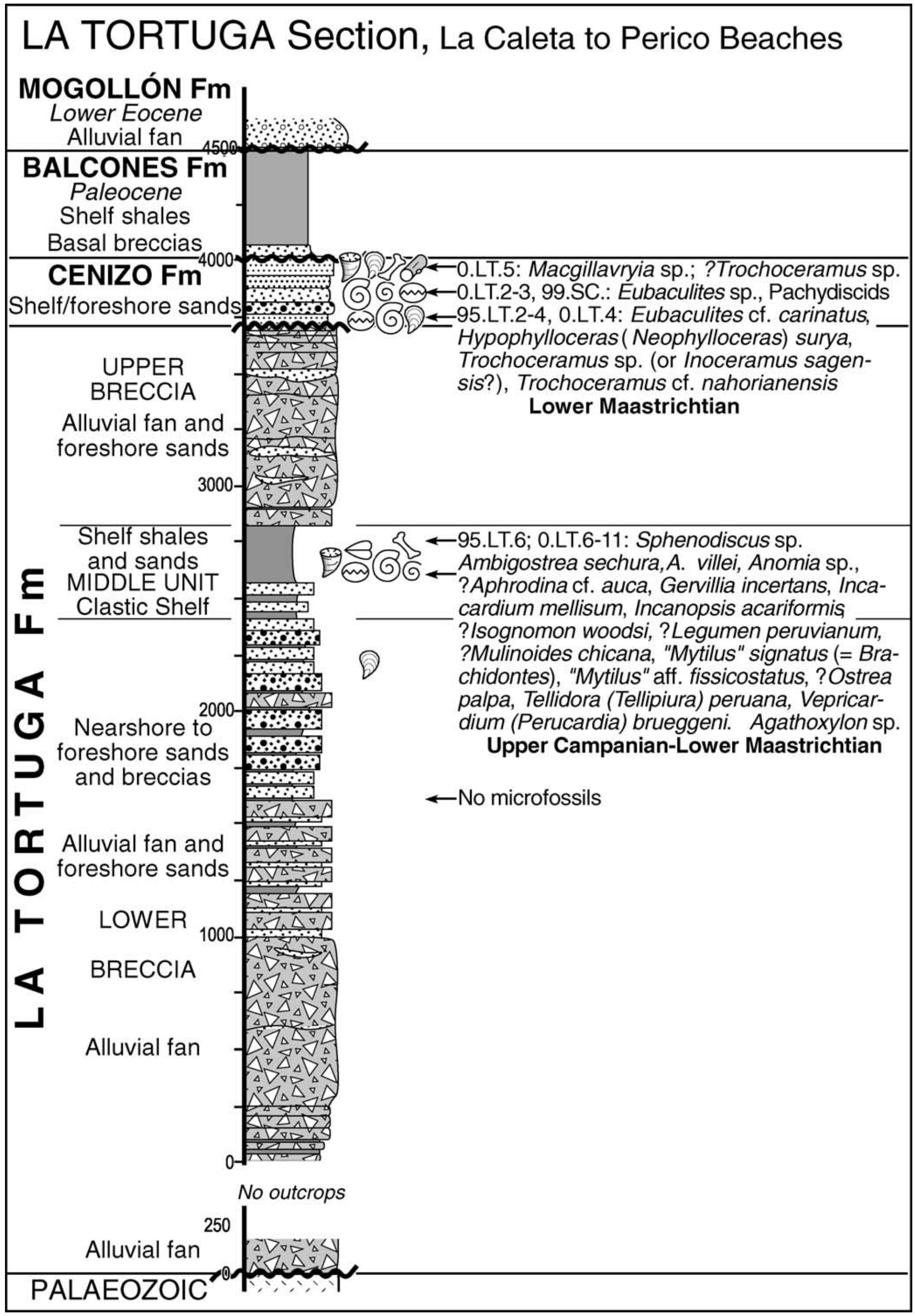

Fig. 7. Section of the La Tortuga and Cenizo formations in the Paita area of northwestern Peru with location of diagnostic taxa.

In the Western Cordillera at 1°45′S (near Huangupud), we collected the ammonites *Exiteloceras* sp. (99.G.74, 99. G.75) of Campanian age and *Hypophylloceras* (*Neophylloceras*) sp. (99.G.75), comparable to *H. (N.) surya* from the lower El Cenizo Formation of northern Peru. This association supports a late Campanian–early Maastrichtian age for the Yunguilla Formation.

In the Cuenca area (Fig. 1), the ammonites *Sphenodiscus peruvianus* Gerth, 1928, and *Solenoceras* sp. indicate an early Maastrichtian age for part of the Yunguilla Formation (Howarth in Bristow and Hoffstetter, 1977; Pratt et al., 1998). In that region, a few kilometers SSE of Azogues, we collected a fragment of *Glyptoxoceras* sp. (Santonian–Maastrichtian; Wright, 1996) or *Neoglyptoxoceras* sp.

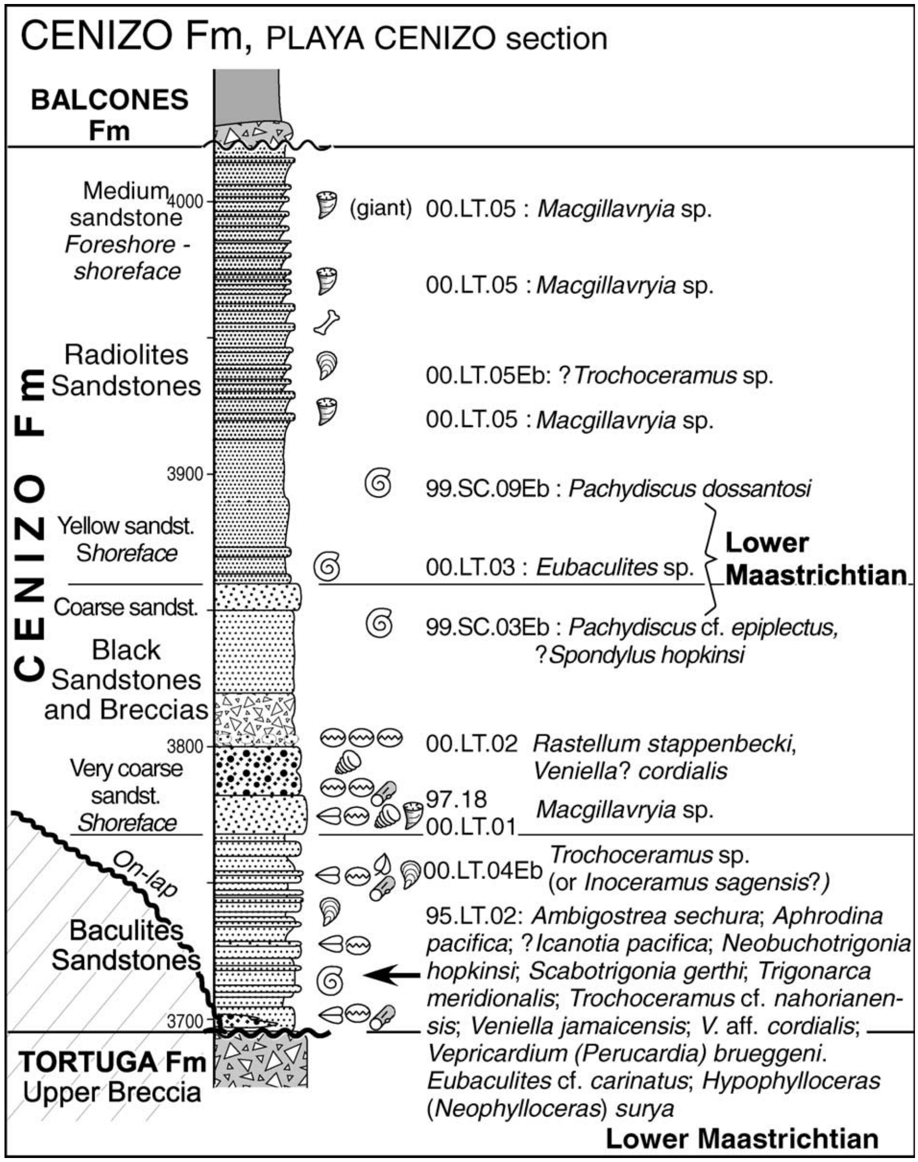

Fig. 8. Section of the Cenizo Formation in the Paita area of northwestern Peru with location of diagnostic taxa.

(lower–middle Campanian; Wright, 1996). In addition, 12 km ENE of Cuenca (El Descanso), we collected a *Diplomoceras* sp. (late Campanian–Maastrichtian; Küchler and Odin, 2001) (02.C.52) and two fragments (02.C.53) of *Glyptoxoceras* sp. or *Neoglyptoxoceras* sp.

According to these data, the Yunguilla Formation is probably of late Campanian–early Maastrichtian age and therefore coeval with the marine transgressions recognized in the Paita and Celica–Lancones areas.

5. Correlations and tectonic implications

Ages for the maximum flooding events are those applied to European basins as determined by Hardenbol et al. (1998), who revised the relative sea level maxima of Haq et al. (1987).

5.1. Turonian–Coniacian

A latest Turonian–early Coniacian maximum flooding event is clearly manifested in the backarc basins according to data from the río Misahuallí and Rentema sections. Because of late Albian and Santonian deformations, the event is poorly expressed in the forearc zones. It is also poorly documented in the Andean areas, though Coniacian marine faunas are widely known. Haq et al. (1987) and Hardenbol et al. (1998) mentioned a significant maximum flooding event near the Turonian–Coniacian boundary (89–88.5 Ma), which fits well with our data (Fig. 9).

The end of carbonate shelf sedimentation and the beginning of fine-grained clastic sedimentation is dated as latest Turonian–earliest Coniacian in Ecuador (Misahuallí) and late Turonian in the Rentema area in Peru. This change

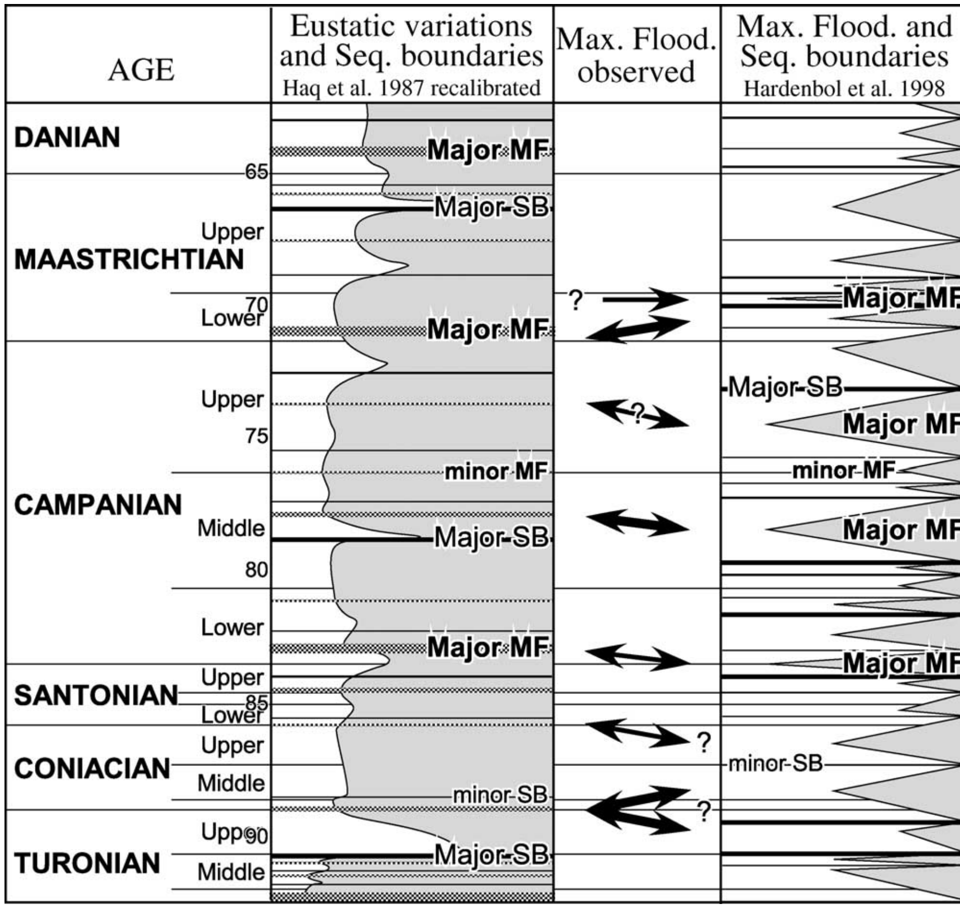

Fig. 9. Comparison of marine transgressions recognized in northern Peru and Ecuador and eustatic sea level fluctuations identified by Haq et al. (1987) [recalibrated by Hardenbol et al., 1998] and Hardenbol et al. (1998).

in sedimentation has been interpreted as the beginning of the ‘Peruvian’ tectonic phase (Jaillard, 1994; Sempéré, 1994).

5.2. Santonian

A Santonian maximum flooding event is locally manifested in the eastern basins of Ecuador and northern Peru. According to the faunas collected at Pongo de Rentema, it appears to be of late Coniacian–early Santonian age. No Santonian maximum flooding event is known to have occurred in the forearc zones of northern Peru and Ecuador, but an early Santonian transgression was identified in the forearc zone of southern Peru (Vicente, 1981; Jaillard, 1994). Transgressions or high sea level periods of Santonian age are known from Venezuela (Helenes et al., 1998; Helenes and Somoza, 1999) and Colombia (upper Magdalena Basin, Vergara, 1997; eastern basin, Guerrero and Sarmiento, 1996).

The earliest Santonian age of the eustatic maximum flooding (ca. 86–85 Ma), quoted by Haq et al. (1987) and Hardenbol et al. (1998), is consistent with our data (Fig. 9). Because of uplift during the ‘Peruvian’ tectonic phase, the middle Santonian–early late Santonian maximum floodings mentioned by them are unknown in the Andean margin of northern Peru and Ecuador.

5.3. Campanian

A late Santonian–early Campanian maximum flooding event has been recognized only in the eastern part of the Celica–Lancones area and locally in the central part of the Oriente Basin of Ecuador (upper part of the M-1 shales, below the M-1 sandstones). In the Celica–Lancones area, it unconformably overlies volcanic rocks deformed by the mid and Late Cretaceous tectonic events. In the Oriente Basin, it follows a depositional break comprising part of the Santonian (Raynaud et al., 1993; Robertson Research, 1997). This late Santonian–early Campanian marine transgression was probably enhanced by tectonic subsidence and seems to represent the first stage of the regional Campanian transgression that conceals the ‘Peruvian’ deformations.

An early Campanian maximum flooding event is locally known, for example, from the eastern basin of northern Colombia (San Antonio Formation, Guerrero and Sarmiento, 1996) and the eastern Gulf Coastal Plain of North America (Mancini et al., 1996) but has not been identified in

Venezuela (Helenes et al., 1999; Helenes and Somoza, 1999). This transgression might correspond to the major transgression identified by Haq et al. (1987) and recalibrated by Hardenbol et al. (1998) near 83.5–83 Ma (Fig. 9). This major transgression is only locally manifested, which indicates that the Andean margin already was uplifted and deformed by the 'Peruvian' deformations.

The mid Campanian–early late Campanian transgression was a major event that definitely concealed the 'Peruvian' deformations. According to available data, this transgression is manifested in the eastern basins of Ecuador (M-1 sandstones) and Peru (lower Vivian Formation), as well as in the forearc zones of northwestern Peru (La Mesa Formation) and southwestern Ecuador (upper El Naranjo Formation). Farther south, thin marine layers that contain selachians, scarce bivalves, and charophytes have been correlated with the mid Campanian–early late Campanian transgression (Jaillard et al., 1993). In the forearc zones, this widespread transgression seems characterized by the deposition of open-marine shelf limestones. Because emergence occurred after the early Santonian at Pongo de Rentema (see Bengtson, 1988), the age of the 'Peruvian' tectonic phase can be bracketed between mid Santonian and mid Campanian times.

The mid to early late Campanian transgression is known in the whole east Pacific area, from the Antarctic Peninsula (Askin et al., 1991) and Argentina (Lagarreta et al., 1989; Barrio, 1990) to Colombia and Venezuela (Barrio and Coffield, 1992; Guerrero and Sarmiento, 1996; Vergara, 1997; Helenes et al., 1998) and Central and North America (e.g. Gill and Cobban, 1973; Molenaar and Rice, 1988; Michaud et al., 1992). It also is manifested in the South Atlantic basins, such as the Sergipe (Bengtson et al., 1996) and Pernambuco–Paraíba (Muniz, 1993) basins. Because the 'mid' Campanian maximum flooding event reached the tectonically stable eastern basins of the Andean margin, it probably coincides with a significant eustatic sea level rise. According to Haq et al. (1987) and Hardenbol et al. (1998), mid and late Campanian times were marked by a high average sea level and three sea level rises. Because the late mid Campanian (ca. 78 Ma) and late Campanian (ca. 73.5 Ma) maximum flooding events are considered more significant (Hardenbol et al., 1998), they may correlate with the maximum flooding events recognized herein (Fig. 9).

That this transgression is much more clearly manifested in the forearc zones than in the eastern basins suggests that it was reinforced by tectonically driven subsidence of the forearc zones of northern Peru and Ecuador.

5.4. Maastrichtian

An early Maastrichtian transgression is manifested in the forearc zones of northwestern Peru (lower Cenizo Formation) and western Ecuador (Yunguilla Formation), the Oriente Basin of Ecuador (base of Tena Formation, 'Flysch Limón'), and the East Peruvian Basin (Fundo el Triunfo and Cachiyacu formations; Mourier et al., 1988; Mathalone and Montoya, 1995). The transgression has been identified in most eastern areas of Peru (Areniscas de Azúcar, Puquín, and upper Vilquechico formations; Koch and Blissenbach, 1962; Jaillard et al., 1993; Carlotto, 1998) and in Bolivia (El Molino Formation), where it is dated as early Maastrichtian by paleomagnetism coupled with a radiometric date (72 Ma, Sempéré et al., 1997). However, in many eastern areas, stratigraphic data are not accurate enough to determine whether this transgression correlates with the early Maastrichtian transgressions recognized in the forearc zones. In the northern part of the Ecuadorian Subandean zone (Bermejo), the Maastrichtian Tena Formation seems to record successive marine transgressions (Faucher et al., 1971; Jaillard, 1997a).

Early Maastrichtian transgressions are well known from the Salta (Salfity and Marquillas, 1994), Neuquén (Lagarreta et al., 1989; Barrio, 1990), and Magallanes (Biddle et al., 1986) basins of Argentina (see Malumián and Ramos, 1984; Uliana and Biddle, 1988). They are also well documented in northeastern Colombia (Guerrero and Sarmiento, 1996), Venezuela (Helenes et al., 1998), and North America (Gill and Cobban, 1973; Molenaar and Rice, 1988); and in the Pacific guyots, where Arnaud-Vanneau et al. (1995) recognized two maximum flooding events of early Maastrichtian age (sequence boundaries at 73–74 and 71 Ma, respectively). These data indicate that the widespread early Maastrichtian maximum flooding event recognized on the Andean margin coincides with a major eustatic rise, which could correspond to the earliest Maastrichtian major maximum flooding event of Haq et al. (1987) (71 Ma, according to the calibration by Hardenbol et al., 1998; Fig. 9). According to Hardenbol et al. (1998), the early Maastrichtian major maximum flooding event is younger (ca. 69.5 Ma).

Later Maastrichtian transgressions have been recognized in southern Argentina (Austral and Neuquén basins; e.g. Biddle et al., 1986; Barrio, 1990), eastern Colombia (Guaduas Formation; Barrio and Coffield, 1992; Guerrero and Sarmiento, 1996), Venezuela (Helenes and Somoza, 1999), and southern North America (early late Maastrichtian; Mancini et al., 1996). However, because of poor biostratigraphic control and only local records, correlation of these events is difficult. Hardenbol et al. (1998) mention a significant maximum flooding event during the late early Maastrichtian (69.5 Ma), which might correlate with the late(?) early Maastrichtian upper Cenizo transgression of northwestern Peru.

Conglomerates and turbidites characterize the Maastrichtian deposits of the forearc zones of northern Peru and southern Ecuador. In northwestern Peru, the late Campanian transgressive marls, limestones, and sandstones of the upper La Mesa Formation grade into shelf sandstones and conglomerates. The late Campanian–early Maastrichtian La Tortuga Formation consists of a 3500 m thick series of breccias (Olsson, 1944; Bengtson and

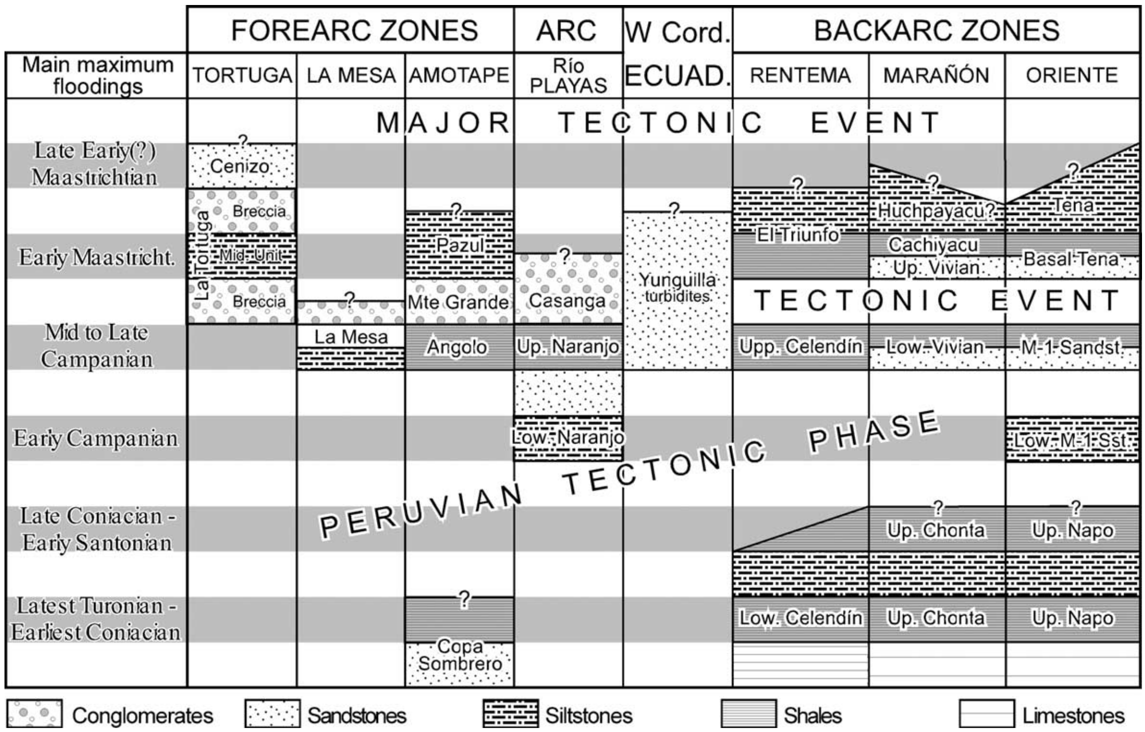

Fig. 10. Tentative correlation of the main maximum flooding events, considered timelines, across the Andean margin.

Jaillard, 1997). In the Celica–Lancones area, the late Campanian beds (Angolo, Zapotillo, and El Naranjo formations) are conformably overlain by coarse-grained conglomerates (Monte Grande and Casanga formations, respectively; Olsson, 1934; Baudino, 1995; Jaillard et al., 1996, 1999), which in turn are overlain by early Maastrichtian deposits (Pazul and Cazaderos formations). In these forearc areas, the lack of younger deposits suggests that they emerged by the middle–late Maastrichtian. In the Cordillera of Ecuador, the early Maastrichtian is marked by turbiditic deposits (Yunguilla Formation), and no late Maastrichtian beds have been identified. In the backarc basins, the late Maastrichtian is marked by either deposition of fine-grained redbeds or hiatuses (Jaillard, 1997a).

Such coarse-grained deposits express important tectonic activity in the forearc zone, which could be related to rapid wrench movements evidenced between 70 and 60 Ma in the arc zone of central and northern Peru (Bussel and Pitcher, 1985). Late Maastrichtian tectonic activity is further documented by a thermal event (75–60 Ma; Litherland et al., 1994) and rapid uplift around 65 Ma (Spikings et al., 2001) recorded in the Eastern Cordillera of Ecuador, as well as by a latest Maastrichtian deformational phase manifested in central Colombia (Cheilletz et al., 1997). They seem to correlate with the accretion of an oceanic terrane known in central Ecuador (Jaillard et al., 2004).

No marine deposits that correlate with the major early Danian sea level rise (Haq et al., 1987; Fig. 9) have been recognized on the Andean margin. However, the poor chronostratigraphic data available for the Paleocene subaerial deposits do not allow their accurate correlation with the tectonic and sedimentary events recorded in the forearc zones.

6. Conclusions

Six maximum flooding events are recognized on the Andean margin of northern Peru and Ecuador (Fig. 10): (1) latest Turonian–early Coniacian, (2) late Coniacian–early Santonian, (3) early Campanian, (4) mid Campanian–early late Campanian, (5) early Maastrichtian, and (6) terminal early Maastrichtian. The major marine transgressions occurred in the latest Turonian–early Coniacian, mid Campanian–early late Campanian, and early Maastrichtian, a pattern that coincides broadly with known eustatic sea level rises (Fig. 9).

Although most of the marine transgressions on the Andean margin coincide in time with eustatic sea level rises, their magnitudes do not correspond with those predicted by the eustatic charts of Haq et al. (1987) or Hardenbol et al. (1998) (Fig. 9). For example, the major mid Campanian–early late Campanian transgression on the Andean margin may correlate with either the mid Campanian (78.5 Ma) or the early late Campanian (74.5 Ma) sea level rises of Hardenbol et al. (1998), whereas the major latest Santonian–earliest Campanian eustatic transgression (Haq et al., 1987; Hardenbol et al., 1998) has been recorded only locally in the Andean margin. Therefore, regional or local tectonic movements probably account for the absence of traces of the mid Santonian, late Campanian, and early Danian sea level rises on the Andean margin, as well as for the enhancement of the mid Campanian and early Maastrichtian transgressions.

With respect to the tectonic evolution of the Andean margin, we emphasize several results. First, fine-grained clastic sedimentation in the Oriente and East Peruvian basins began in the mid Turonian–earliest Coniacian (Fig. 10), which we take as the first manifestation of the 'Peruvian' tectonic phase. Second, the Campanian regional transgression in the Peruvian–Ecuadorian forearc zones concealed the 'Peruvian' deformational event, which occurred between the late Coniacian and mid Campanian (Fig. 10), probably during the mid Santonian–earliest Campanian interval (ca. 85–82 Ma). Third, the 'Peruvian' tectonic phase caused a paleogeographic upheaval, as is indicated by the subsequent development of a NNE-trending forearc basin that extended at least from Paita to Quito (5°30′S-0°). Fourth, in the forearc zones, only short-lived marine transgressions are recorded in the late Campanian and Maastrichtian because of nearly continuous tectonic activity that seems to have culminated in the latest Campanian. Fifth, a widespread, regional, late Maastrichtian unconformity indicates that a major tectonic event affected the whole Andean margin at this time (68–65 Ma; Fig. 10).

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