Cretaceous Research (1993) **14**, 585–605

The Cenomanian–Turonian transition on the Peruvian margin

***‡E. Jaillard and ‡A. Arnaud-Vanneau**

**ORSTOM, CS 1, UR 1H, 213 rue La Fayette, F-75480 Paris cedex 10*
‡Institut Dolomieu, 15 rue Maurice-Gignoux, F-38031 Grenoble cedex

Accepted 26 July 1993

In Peru, various depositional sequences can be recognized during the late middle Cenomanian to early Coniacian timespan, most of which seem to have an eustatic origin. For instance, the early late Cenomanian, late early Turonian and early Coniacian maximum floodings identified in Peru coincide with well-known global eustatic events. The *Mammites nodosoides*-bearing marls probably correspond to the major Cretaceous marine transgression on the Peruvian margin. However, tectonic movements may have occurred during late Cenomanian times. The widespread hiatus of latest Cenomanian to earliest Turonian age, probably owing to a significant lowering of sea level, may have been amplified by tectonically-induced erosion. Restricted to disaerobic conditions reach a maximum close to the Cenomanian–Turonian boundary and coincide with the well-known oceanic anoxic event. However, anoxia seems to have been less important than elsewhere, probably because of better oceanic circulation. Large benthonic foraminifera are represented by *Pcrouvianella peruviana*, *Archaecyclus* sp. and species of *Sellialveolina*. The remarkable persistence of *P. peruviana* through the Cenomanian–Turonian boundary crisis could be related to the less drastic anoxic conditions, responsible for continuous carbonate shelf sedimentation.

Key Words: Peruvian margin; late Cenomanian; Turonian; sequence stratigraphy; tectonics; benthonic foraminifera.

1. Introduction

The Peruvian continental margin is considered to be a typical active margin, where subduction of the palaeopacific oceanic plate has been occurring since at least Late Jurassic times. Although the Mesozoic–Cenozoic magmatic activity and the Tertiary–Quaternary tectonic history have been widely studied, the sedimentary evolution and micropalaeontology of the Cretaceous series are still poorly known.

The Cenomanian–Turonian boundary is a very peculiar geological period characterized by a wide variety of events collectively interpreted as the result of global eustatic or large-scale tectonic crises. In most of the Tethyan and Atlantic domains, latest Cenomanian to earliest Turonian beds are characterized by widespread stratigraphic gaps or sedimentary discontinuities that coincide with the end of the platform carbonate sedimentation, by anoxic deposits of major significance and interest or by mass-extinction of most species of large benthonic foraminifera, or by some combination of the above.

The aim of this paper is to present the sedimentary events recorded on the Peruvian active margin close to the Cenomanian–Turonian boundary, and to compare them with those of other areas in order to determine their regional or global character. We present the results of sedimentological and micropalaeontological studies of some selected late Cenomanian–Turonian sections located in northern, central and southern Peru. For each region, the stratigraphic framework, the sedimentary evolution, its interpretation in terms of sequence stratigraphy, and the biostratigraphic events are presented. Comparisons with other Andean regions and with global events are then attempted and discussed.

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2. Geological setting

During Early to middle Cretaceous times, the central Andean margin was occupied by an isolated sedimentary basin, the Central Andean Basin, which covered most of eastern Ecuador and the whole Peruvian region and terminated southwards in Bolivia (Figure 1). It was separated from the northern, Colombian–Venezuelan Basin by a topographic high, and was bounded on the east by the Guyanese and Brazilian shields. Connexion with the southern Andean troughs probably occurred through the Pacific Ocean.

During the middle Cretaceous, the Central Andean Basin included from west to east (Figure 2): (1) a westernmost, mainly volcanic coastal zone, interpreted as either a marginal basin (Atherton *et al.*, 1983; Atherton, 1990) or, more probably, a magmatic arc (Soler, 1991). The volcanic activity, mostly of Albian age, was followed by the emplacement of a major Late Cretaceous plutonic arc, the coastal batholith (Beckinsale *et al.*, 1985);

(2) a western, subsident trough infilled by thick marine, mainly calcareous deposits;

(3) a topographic high which received less sediment; and

(4) an eastern basin, shallowing eastwards, which received continental to marine terrigenous sedimentation.

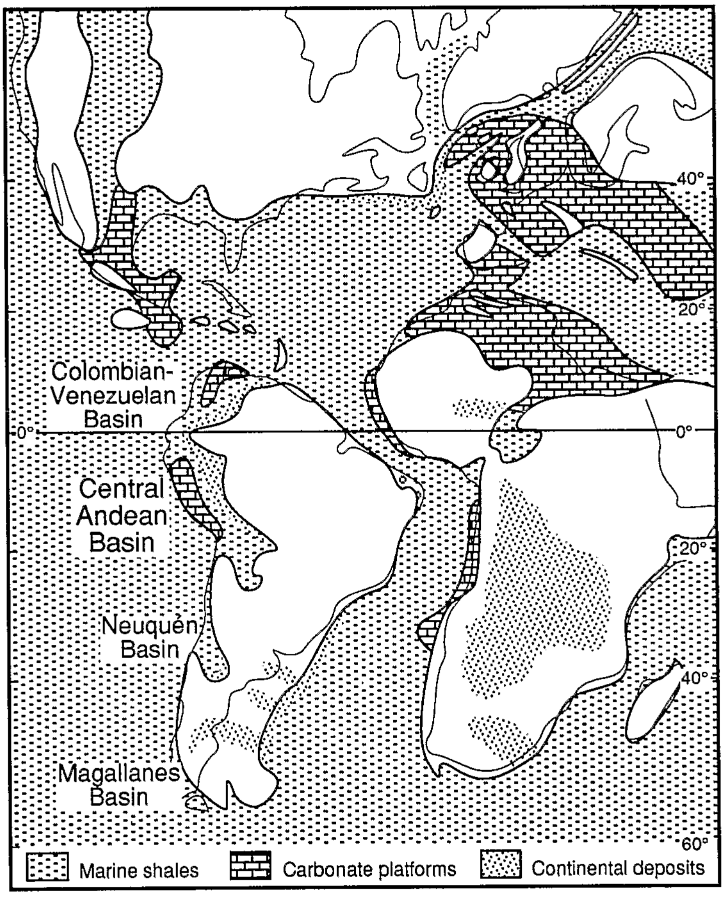

Figure 1. Location of the central Andean Basin during Cenomanian–Turonian times (after Emery & Uchupi, 1984, modified).

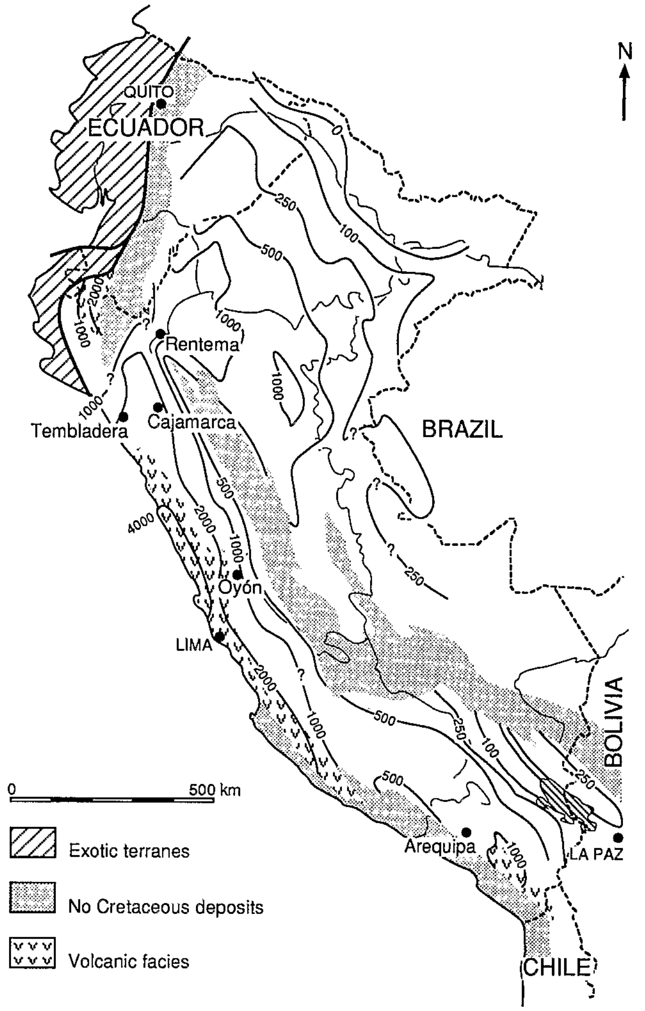

Figure 2. Isopach map of the deposits of late Aptian to late Turonian age in the Central Andean Basin, and location of the studied sections.

In the western trough, the Tithonian–Senonian timespan can be divided into four major periods (Jaillard, in press):

Tithonian–Berriasian. In northern Peru, a deep, fault-bounded sedimentary basin was created and infilled by thick clastic sediments deposited in pelagic to deltaic environments, whereas southern Peru became emergent (Batty *et al.*, 1990). These extensional tectonic events are interpreted as the result of a major geodynamic reorganization (Jaillard *et al.*, 1990; Jaillard, in press).

Valanginian–Aptian. A widespread clastic system of eastern provenance invaded the whole Central Andean Basin, depositing well-sorted clean sandstones. From east to west, the depositional environment evolved from fluvial to shoreline. Subsequent to the latest Jurassic tectonic subsidence, an important thermal subsidence occurred in northern Peru, whereas southern Peru gently subsided.

Late Aptian–late Turonian (middle Cretaceous). The Late Cretaceous eustatic marine transgressions led to the development of four major lithologic sequences. In the western basin, these consist of basin marls and shelf limestones. In the eastern domain, the sequences commonly end with deltaic sandstones, owing to the reduced depth of deposition and the important clastic supply. In northern Peru, the continuing thermal subsidence explains the 2000 to 3000 m-thick middle Cretaceous deposits, in contrast to the 500 to 700 m-thick south Peruvian coeval series (Figure 2). The coastal volcanic centres were active during the late Aptian–Albian interval. Their progressive tectonic closure between middle Albian and early Cenomanian times (Cobbing *et al.*, 1981) is known as the Mochica tectonic phase (Mégard, 1984; Jaillard, in press).

Senonian–Paleocene. Near the Turonian–Coniacian boundary, the beginning of the Andean orogeny (Peruvian tectonic phase; Steinmann, 1929) led to: (1) the establishment of a detrital, shaly sedimentation; (2) the progressive and diachronous emergence of the margin; and (3) the eastward shift of the depocentres (Jaillard, in press; Sempere, in press).

From Paleocene to present, the sedimentation is continental.

3. Presentation, methodology

Presentation of the Cenomanian–Turonian sections

In northern Peru, among various studied sections we selected those of Rentema, Cajamarca and Tembladera, which are well-exposed, fossiliferous, and characterize distinctive palaeogeographic settings. The Rentema section, well-exposed along the Bagua–Chachapoyas road, is located near the boundary between the eastern and western basins, where the topographic high disappears (Figure 2). It is marked by an abundant easterly-derived argillaceous supply, and by a high subsidence rate. The ammonite determinations are those mentioned by Córdova (1986). The Cajamarca section is a condensed section located farther south (Figure 2). The column presented results from the superposition of the late Cenomanian–early Turonian formations studied 20 km ENE of Cajamarca, and of the middle to late Turonian deposits exposed near Bambamarca, 50 km north of Cajamarca. We used the ammonite determinations of Benavides (1956). Tembladera, the westernmost well-exposed section at this latitude (Figure 2), is very fossiliferous and crops out along the road to Cajamarca. The identifications by Benavides (1956) were supplemented by new determinations of ammonites examined by W. J. Kennedy. Unfortunately, neither the microfacies nor the ammonites can be easily analysed, because of the low-grade metamorphism and hydrothermal alterations caused by numerous intrusions.

The Oyón section is located about 100 km north of Lima (Figure 2), and is one of the westernmost sections of central Peru. The late Albian–late Turonian interval is represented by about 1500 m of massive platform limestones (Jumasha Formation; Wilson, 1963). Previous field studies were made by Romani (1982), Jaillard (1986) and Nuñez del Prado (1989).

In southern Peru, the Arequipa section (Figure 2) consists of a series of massive platform limestones of early Albian to late Turonian age (Arcurquina Formation; Benavides, 1962; Dávila, 1988). It has been measured 30 km northwest of Arequipa, at the type locality of Cerro Arcurquina.

Methodology

The identification of the depositional sequences was made using sedimentological and palaeontological criteria. These differ significantly according to the lithology of the deposits.

Marly sections. The sections consisting of marls alternating with thin-bedded limestones were analysed according to field observations.

The transgressive systems tract deposits are generally marked by the increase of sandy, locally glauconitic, deposits. They are made up of marl-limestone alternations that are increasingly marly upwards. At the top of the limestone beds, short-lived sedimentary hiatuses are represented by oyster coquinas and numerous borings evidencing an early lithification. The frequent preservation of desiccation structures is considered to be a result of the increasing accommodation rate which prevented emergence-related erosion, thus permitting the preservation of intertidal deposits. Hardgrounds are frequent in condensed sections. The lithologic discontinuity between the limestones and marls is attributed to the maximum eustatic sea level rise.

Maximum flooding surfaces are represented by thin marly intervals containing ammonites and/or outer shelf fossils such as large bivalves. They are generally located a few metres above the last limestone bed. The highstand systems tract deposits probably consist of interbedded marls and limestones becoming less marly upwards. These deposits bear sea-urchins, gastropods and bivalves.

Shelf limestone sections. The shelf sections have been studied through detailed field observations, then completed by thin section analyses. The depositional sequences were defined using the following criteria.

The beginning of the transgressive systems tract is commonly marked by a succession of massive limestone beds separated by minor erosional surfaces associated with intraclasts and/or detrital quartz. The amount of bioturbation, echinoderms and small unidentifiable hedbergellids increases upwards; the texture usually grades from packstone-grainstone to mudstone-wackestone; and the number of benthonic elements is abundant or slightly decreasing. The presence of oysters and inoceramids is an indication of the more open and agitated environment typical of the transgressive trend. These deposits are progressively and rapidly overlain by marl-marly limestone alternations, which comprise the upper part of the transgressive systems tract. These are marked by a significant decrease in the benthonic foraminifera and by the disappearance of algae. Large bivalves (oysters, inoceramids) are usually present, as well as bioclasts and detrital quartz.

The maximum flooding surfaces are generally located within the marls. They are indicated by the peak occurrence of echinoderms, small planktonic and benthonic foraminifera, and by the disappearance or scarcity of algae and miliolids. The rare ammonites are generally found within these levels.

The highstand systems tract is represented by interbedded marls and limestones becoming less marly upwards. Limestone beds are rich in algae, miliolids, benthonic foraminifera, and pellets or oolites. The texture grades from mudstone-wackestone to packstone-grainstone, and finally to laminated mudstones showing intertidal or desiccation features at the top.

Organic matter/restricted environment. The content of organic matter was only qualitatively estimated using field observations including the darkness of the deposits, the fetid smell, or the abundance of pyrite and gypsum. Obviously, such observations do not enable one to distinguish the effects of a locally restricted environment from those connected with regional anoxic events, or to determine the origin and nature of the organic matter.

4. Stratigraphic framework

Northern Peru

In the western trough of northern Peru, a thick and highly fossiliferous succession of marls and limestones allowed Benavides (1956) to define a rather precise ammonite zonation as well as a detailed stratigraphy based on the lithologic sequences. However, palaeontological correlations are sometimes difficult with the Tethyan or European stratigraphic standards, and the work of Benavides must be examined, taking into account the subsequent palaeontological and stratigraphical revisions. The middle Cenomanian carbonate platform (Mujarrún Formation) was dated by *Exogyra* species, and by specifically unidentifiable acanthoceratids (Benavides, 1956).

It is overlain by a thick series (100 to 400 m, Romirón Formation) of yellowish and brownish to rusty marls, intercalated with thin-bedded detrital limestone bearing oyster coquina and abundant desiccation features. Benavides (1956) identified several *Acanthoceras* species, *Forbesiceras* sp., *Lissoniceras mermeti* and *Neolobites kummeli* Benavides. This latter is equivalent to *N. vibrayeanus*, an early late Cenomanian species in Europe (Kennedy & Juignet, 1981). Since they are associated with, or occur above, *N. vibrayeanus*, the *Acanthoceras* species determined by Benavides (1956) would need to be revised. Hence, although the Romirón Formation was ascribed to the late Cenomanian by Benavides (1956), the ammonite content rather indicates a latest middle Cenomanian to early late Cenomanian age. Locally (Cajamarca, Rentema?), the lack of latest Cenomanian fauna and/or the condensed section strongly suggest a sedimentary gap during part of the late Cenomanian.

The overlying marls (10 to 200 m, Coñor Formation) differ from the Romirón Formation in their grey colour, the scarcity of oyster coquinas and the abundance of inoceramids. Benavides (1956) noted the presence of *Mammites nodosoides*, *Coilopoceras jenksi* Benavides, *Vascoceras* aff. *silvanense*, *Broggiceras olssoni* Benavides, *B. humboldti* Benavides, *Hoplitoides inca* Benavides, some species of *Pseudoaspidoceras* and *Thomasites*, as well as *Inoceramus labiatus* and assigned the marls an Early Turonian age (Figure 3). *Hoplitoides inca* Benavides is now considered to be a synonym of the lower Turonian species *Wrightoceras munieri* (Kennedy *et al.*, 1987). On the other hand, Schöbel (1975) equated both *Broggiceras olssoni* Benavides and *B. humboldti* Benavides with *Vascoceras cauvini*, a species of latest Cenomanian age (see also Berthou *et al.*, 1985; Zaborski, 1989). Nevertheless, in the Rentema section, Peruvian palaeontologists have identified *B. olssoni* within and above the beds with *M. nodosoides* (Córdova, 1986). Therefore, either the equivalence of *B. olssoni* and *V. cauvini* is not correct, or Rentema's identifications need revision. In this paper we consider that the Coñor Formation may locally include latest Cenomanian beds. However, in the Cajamarca section, the occurrence of *M. nodosoides* near the base of the formation would indicate that latest Cenomanian and earliest Turonian deposits are lacking there.

The overlying micritic, light-coloured shelf limestones (40 to 600 m, Cajamarca Formation) include two marl layers, thus defining three lithologic sequences (Jaillard, 1985; 1987). Both marly layers yielded *Coilopoceras newelli* Benavides (Benavides, 1956; and samples determined by W. J. Kennedy), indicating a late Turonian age (Figure 3). The previous identification of *Helvetotruncana helvetica* (Jaillard, 1987) has not been confirmed in spite of extensive samplings studied by M. Caron.

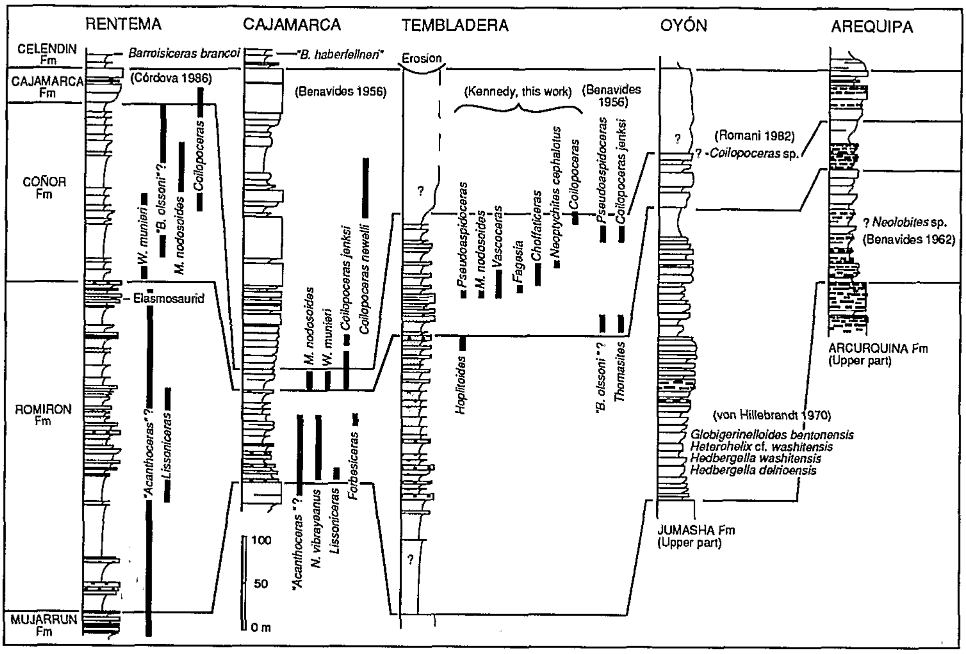

Figure 3. Stratigraphic data for the late Cenomanian–Turonian sections of the Peruvian margin.

The Cajamarca Formation is overlain by a highly fossiliferous marly formation. Benavides (1956) identified *Buchiceras bilobatum* and various species of *Heterotissotia* and *Barroisiceras* of early Coniacian age, among them *Barroisiceras haberfellneri* (Figure 3). The latter may correspond to the early Coniacian indicator *Forresteria (Harleiceras) petrocoriensis* (see Kennedy, 1983; Hancock, 1991).

Central Peru

In central Peru, the late Albian–Turonian interval is represented by a 300 to 1500 m-thick series of massive shelf limestones, known as the Jumasha Formation (Wilson, 1963). In Oyón, the lower part of the Jumasha Formation includes three marl-limestone lithologic sequences (Jaillard, 1986). The second of these yielded *Merlingina cretacea* of Cenomanian age (Romani, 1982), whereas the upper one contains *Sellialveolina* sp., suggesting a middle to late Cenomanian age. Farther south, the base of the marly upper part of the formation was dated by ostracods and planktonic foraminifera of probable middle to late Cenomanian age (von Hillebrandt, 1970). Finally, in Oyón, *Coilopoceras* sp. has been found about 150 m below the top of the formation (Romani, 1982), thus indicating a Turonian age for the upper part of the Jumasha Formation (Figure 3).

Southern Peru

In the southern part of the West Peruvian Trough, the entire late Aptian–late Turonian timespan is represented by light coloured, massive shelf limestones (Arcurquina Formation; Benavides, 1962). In the lower part of this formation, Dávila (1988) mentioned *Parahoplites* sp. and *Oxytropidoceras carbonarium* of late Aptian–earliest Albian and middle Albian age, respectively. *Neolobites* sp. was found in the upper part of this formation, indicating the late part of the Cenomanian (Benavides, 1962) (Figure 3).

5. Sedimentology of the Cenomanian–Turonian transition

Northern Peru

Romirón Formation: Using the above mentioned sedimentological criteria, the Romirón Formation can be divided into three sequences. Because of poor outcrop conditions, the first sequence has not been studied in Tembladera (Figure 4).

In Rentema, the first sequence (Ro1, Figure 4) begins with glauconitic and sandy marls interbedded with marly limestones. For each alternation, glauconite and quartz increase from base to top, whereas detrital supply decreases upwards in the sequence. In the Rentema surroundings, the limestone beds exhibit trough laminations, oyster coquinas, root moulds, and desiccation structures (Córdova, 1986). This transgressive systems tract is well developed there, because of the combined high subsidence and sedimentation rate. In Cajamarca, it is represented by thin, sandy deposits, sometimes interrupted by hardgrounds. The maximum flooding deposits are characterized by yellowish marls containing *Lissoniceras mermeti* and *Neolobites vibrayeanus* (Benavides, 1956; Córdova, 1986). The highstand systems tract comprises sandy, marl-limestones alternations. In Rentema, secondary gypsum is present. In all sections, the Ro1 highstand systems tract ends with emergent deposits (Figure 4).

A second sequence (Ro2, Figure 4) is characterized by abundant sands, dark deposits, and an increasing number of oyster coquinas. Except in Tembladera, the top of the Ro2 highstand systems tract parasequences is marked by desiccation features. In Rentema, secondary gypsum becomes abundant. Ro2 seems to be less consistent than Ro1 or Ro3.

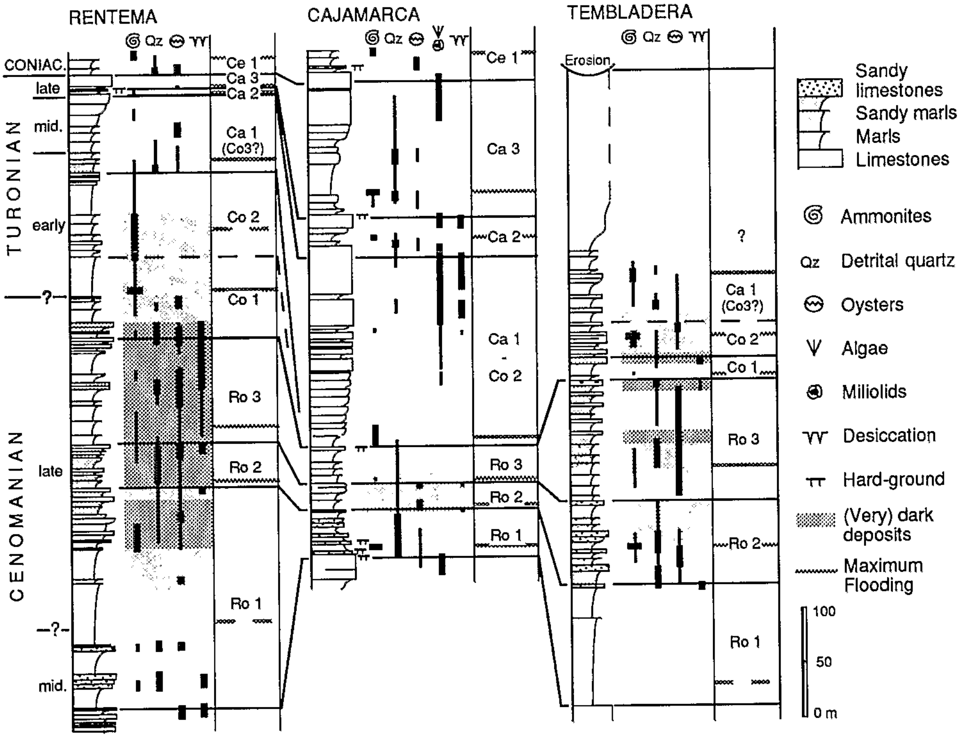

Figure 4. Summarized sedimentological data and interpretation for the late Cenomanian–Turonian sections of northern Peru.

A third major sequence (Ro3, Figure 4) is marked by a general darkening-upward trend, the abundance of oyster coquinas, and locally very abundant secondary gypsum veinlets (Rentema). The occurrence of *N. vibrayeanus* within the maximum flooding deposits indicates an early Late Cenomanian age. In Tembladera, Ro3 seems to have been deposited in a shallower-water environment than the Ro2 sequence, as indicated by desiccation features at the top of the parasequences of the highstand systems tract. In Rentema, the uppermost part of the Romirón Formation consists of black and partly sandy, thickening-upward marl-marly limestone alternations deposited in a tidal environment. They contain an open marine fauna such as ammonites and a plesiosaur (Córdova, 1986), thus supporting their interpretation as having been deposited during the beginning of the transgressive systems tract.

Coñor Formation: Two or three depositional sequences seem to exist within the Coñor Formation (Figure 4).

The first (Co1, Figure 4) is missing in the Cajamarca section, but in Rentema and Tembladera, it is characterized by an abundance of oyster coquinas and indications of a restricted environment (gypsum in Rentema, pyrite and dark limestones in Tembladera). In both cases, the maximum flooding occurs below the appearance of *M. nodosoides*. In Rentema, Córdova (1986) reported the occurrence of *Wrightoceras munieri* and *Broggiceras olssoni* (=*Vascoceras cauvini*?). In Tembladera, Benavides (1956) mentioned a 33 m-thick sequence of yellowish shales and dark limestones containing *Thomasites fisheri* Benavides, *B. olssoni* and *B. humboldti* (=*V. cauvini*?) (Figure 3). Although we could not find these species, they most probably derive from the Co1 sequence, that might, therefore, be partly of latest Cenomanian age.

The second sequence (Co2, Figure 4) is distinguished lithologically by the disappearance of restricted environment indicators (gypsum, pyrite, dark colours), a decrease of detrital quartz supply, and by light-grey colours which contrast with the yellowish colours of the beds below. Oysters become scarce and are replaced by abundant inoceramids. *M. nodosoides* occurs in all of the studied sections, associated with some specimens of *Coilopoceras* and numerous early Turonian ammonite genera (Figure 3). The maximum flooding period seems to coincide with the maximum extent of marine conditions along the Peruvian margin.

In the most complete sections, a third, minor depositional sequence is recognizable, and could represent an important parasequence within the highstand deposits of Co2. In Rentema, the transgressive systems tract consists of partly sandy, iron-rich marls alternating with thin-bedded limestones containing intraclasts in their basal portions (Co3?, Figure 4). These deposits contain large bivalves, sea urchins, gastropods, and abundant oysters, as well as ammonites, notably *M. nodosoides*. In Tembladera, comparable deposits directly overlie the *M. nodosoides*-bearing flooding surface, and contain numerous early Turonian ammonites (Figures 3, 4). The maximum flooding deposits are characterized by an abundance of inoceramids, and by the disappearance of *M. nodosoides*, *Coilopoceras* remaining as the only ammonite genus present. The subsequent highstand deposits constitute the lower Cajamarca Formation (Ca1, Figure 4).

Cajamarca Formation: Three well-correlatable lithologic, marl-limestone sequences corresponding to depositional sequences (Lower, Middle, Upper Cajamarca Members) were identified. The highstand systems tract deposits of the Co2-Ca1 are represented by the light-coloured, massive limestones of the Lower Cajamarca Member (Figure 4).

The abundant tidal deposits associated with erosional surfaces and calcarenitic deposits of the upper part of the first limestone cliff represent the initial deposits of the transgressive systems tract of the Ca2 sequence. They are overlain by bioclastic marls (late transgressive systems tract), the top (maximum flooding) of which yielded various *Coilopoceras newelli.* These progressively grade upwards into the platform limestones of the highstand systems tract of Ca2 (Middle Cajamarca Member).

The beginning of the transgressive systems tract of the Ca3 sequence (Figure 4) is marked by a thin set of erosional surfaces with reworked tidal deposits in the upper part of the massive limestones of the Middle Cajamarca Member. It is followed by a new 'ledge' of bioclastic marls (late transgressive systems tract) containing numerous specimens of *C. newelli* (maximum flooding). The highstand systems tract consists of interbedded marls and limestones, becoming more calcareous and massive upwards (Upper Cajamarca Member). The upper part of the Ca3 highstand systems tract deposits contain numerous benthic organisms locally associated with *Sellialveolina* cf. *drorimensis* (Jaillard, 1987). This foraminiferan seems to disappear at the base of the following transgressive systems tract.

The upper part of the third Cajamarca member is rich in intraclasts and erosional surfaces, or hardgrounds in the less developed sections. It represents the beginning of the transgressive systems tract of a new depositional sequence (Ce1, Figure 4). Just above the third Cajamarca member, a parasequence capped up by a hardground is correlatable through various sections. The Ce1 maximum flooding period is represented by the early Coniacian, "*B. haberfellneri*"-bearing marls of the overlying Celendín Formation (Figure 3).

Central Peru

Five major depositional sequences were identified in the deposits of probable late middle Cenomanian–early Turonian age (Figure 5).

The first sequence begins (early transgressive systems tract) in the upper part of the thick, light-coloured massive limestones of the middle Cenomanian carbonate platform. *Sellialveolina* sp., which appears in the upper part of the mid-Cenomanian highstand systems tract, disappears before the occurrence of the early transgressive systems tract. *Perouvianella peruviana* appears in the maximum flooding deposits (Figure 5), and possibly in the early transgressive systems tract. As suggested by Hillebrandt (1970), this marly layer is correlative with the Romirón Formation (Ro1 sequence) of northern Peru. The highstand systems tract is represented by interbedded marls and limestones, becoming less argillaceous upwards. The overlying limestones are rich in intraclasts, miliolids, *P. peruviana,* oolithized and probably reworked algae, benthonic foraminifera, and secondary dolomitization. These are interpreted as late highstand systems tract deposits.

The second depositional sequence begins (transgressive systems tract) at the top of the oolitic deposits, and is marked by an increasing amount of hedbergellids and echinoderms (Figure 5). Maximum flooding is reached in the overlying marls that contain numerous hedbergellids and are devoid of benthonic foraminifera. The highstand systems tract deposits are represented by marls interbedded with limestones rich in algae, miliolids and *P. peruviana* (Figure 5). Well developed thinning-upward textural cycles (mudstone-wackestone-packstone-wackestone-mudstone, Figure 5) represent parasequences. This sequence is also characterized by a high organic matter content and by sparse secondary dolomitization. It is correlated with the Ro2 sequence of northern Peru.

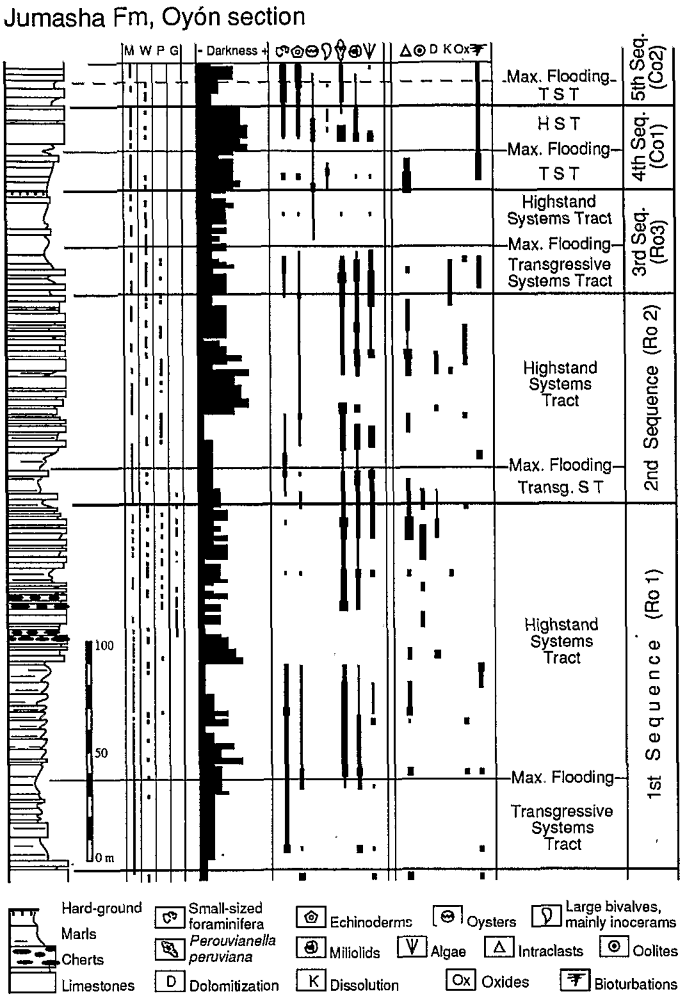

Figure 5. Sedimentological data and interpretation of the upper part of the Jumasha Formation in the Oyón section (central Peru).

The increasing abundance of small hedbergellids is thought to indicate the base of the third sequence (Figure 5). The overlying dark marls are nearly devoid of benthonic elements, except for a few *P. peruviana* that probably represent the maximum flooding. This sequence seems to be abruptly interrupted (eroded?) and is capped up by a ferruginous hardground (Figure 5).

The third sequence is overlain by a 20 m-thick series of dark-coloured bioclastic, marly limestones, interbedded with calcarenitic and sandy marls, with numerous intraclasts in the lower part and abundant bioturbation in the upper part. Oysters, inoceramids, and echinoderms are abundant, and thin sections reveal the presence of unidentified hedbergellids and radiolarians. These deposits are regarded as the transgressive systems tract of a fourth sequence. A poorly exposed outcrop of marl could represent the maximum flooding deposits. The highstand systems tract is represented by black-coloured, fetid-smelling limestones interbedded with bituminous marls (Figure 5). These contain oysters, inoceramids, *P. peruviana* and benthonic organisms. The significant decrease of large bivalves and benthonic organisms in the upper part of the black limestones (Figure 5) seems to be due to anaerobic stress.

Only the base of the fifth sequence has been studied, because of a lack of good exposures. The overlying marls are marked by abundant hedbergellids, organisms indicative of open marine conditions and by a scarcity of benthonic organisms (Figure 5). They probably represent transgressive and/or maximum flooding deposits. We noted that *P. peruviana* is also present. Although decreasing, the organic matter content remains relatively high. Romani (1982) found *Coilopoceras* sp. close to the top of this section. On the basis of this determination together with the abundance of outer shelf organisms, this latter sequence is correlated with the late early Turonian, *M. nodosoides*-bearing Co2 sequence of northern Peru.

Southern Peru

Eight depositional sequences have been identified in the probable late middle Cenomanian–late Turonian interval (Figure 6).

Latest middle to early late Cenomanian sequences: The first sequence overlies very cherty platform limestones of probable mid-Cenomanian age, and therefore correlates with the Ro1 sequence (Figure 6). Oysters and echinoderms are abundant in the transgressive systems tract. Maximum flooding is recorded by dark marly limestones with extensive diagenetic silicification. The highstand systems tract is

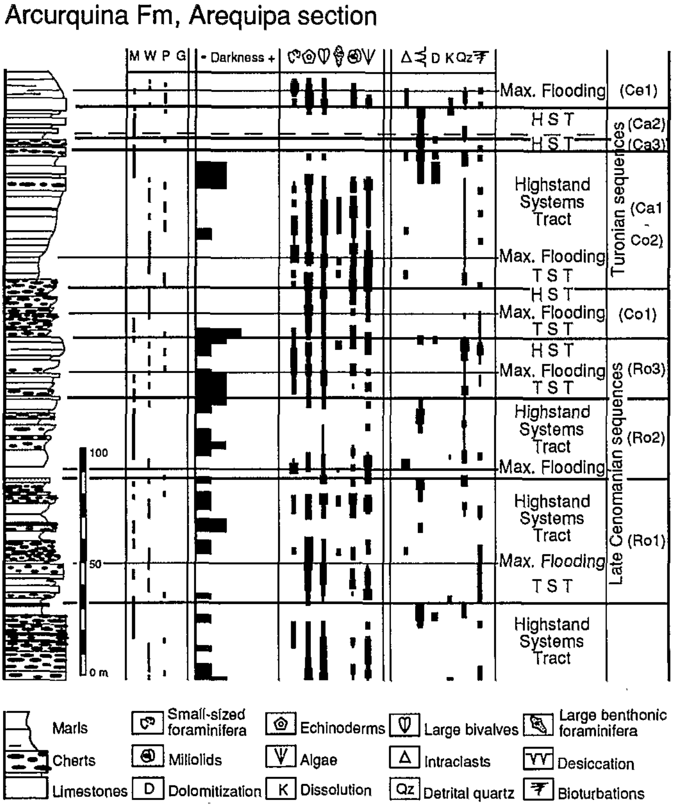

Figure 6. Sedimentological data and interpretation of the upper part of the Arcurquina Formation in the Arcurquina section (Arequipa, southern Peru).

represented by marls and cherty limestones rich in algae and miliolids which are capped by emergent sandy deposits. The second sequence (Ro2, Figure 6) seems to begin with the marls of the maximum flooding. According to Benavides's (1962) description, *Neolobites* sp. should have been found in these strata. The overlying highstand deposits bear desiccation features. The transgressive systems tract deposits of the third sequence (Ro3, Figure 6) correspond to dark marly limestones containing small hedbergellids and oysters. The highstand systems tract deposits are algal-rich marly limestones.

Latest Cenomanian–earliest Turonian sequence: This sequence (Co1, Figure 6) exhibits dark colours in the basal part (transgressive systems tract? and maximum flooding) and very abundant chert in the middle and upper parts (highstand systems tract). Because of the silicification, the structure of the sequence is difficult to analyse, but it appears to belong to an essentially transgressive system. No characteristic fossils were found.

Probable Turonian sequences: The transgressive systems tract of the fifth identified sequence seems to be thin below the well developed maximum flooding deposits (Figure 6). Because of both its stratigraphic position and the disappearance of the oysters and the dark colours, this maximum flooding is correlated with the *M. nodosoides* beds of northern Peru (Co2-Ca1, Figure 6). The highstand systems tract is marked by the appearance of the benthonic foraminiferan *Archaecyclus* sp., which disappears below the tidal deposits of the late highstand systems tract. The upper part of the limestone section is composed of two sequences deposited in a very shallow environment, correlated respectively with the Ca2 and Ca3 sequences of northern Peru (Figure 6). The second of these shows extensive evidence of extensional synsedimentary tectonic activity.

A new transgressive systems tract leads to a well developed flooding surface which is correlated with the "*B. haberfellneri*" beds of northern Peru (Ce1, Figure 6).

Specific associations of benthonic foraminifera:

Large benthonic foraminifera are present at various levels within the studied succession, but they are most abundant in the transgressive systems tracts and in the early highstand systems tracts. They are represented by *Sellialveolina* sp., *Sellialveolina* cf. *drorimensis*, *Perouvianella peruviana* and *Archaecyclus* sp. (Figure 7).

The genus *Archaecyclus*, presently known from the Cenomanian of the Tethys, occurs in middle Turonian strata of southern Peru.

The species *Sellialveolina drorimensis* is known from the middle and late Cenomanian of the Tethys (Schroeder & Neumann, 1985). A closely related species, here referred to as *Sellialveolina* cf. *drorimensis*, is identified in upper Turonian beds of northern Peru. In addition, *Sellialveolina* sp. is present in the middle Cenomanian limestones of central Peru (Figure 7).

Perouvianella peruviana (Figure 7) has been described previously from Peru by Steinmann (1929) and Bizon *et al.* (1975), who mentioned that it is associated with *Neomeris cretacea*. Although *N. cretacea* is most abundant in the Albian and Cenomanian, Bizon *et al.* (1975) considered *P. peruviana* to be characteristic of the Santonian stage. In the Oyón section, if our stratigraphic data are correct, this species is present throughout the late Cenomanian to early Turonian transition, including within the anoxic levels of the Cenomanian–Turonian transition (Figure 5). Therefore, *P. peruviana* could constitute an exceptional example of a large

Figure 7. Middle Cenomanian–Turonian large benthonic foraminifera of the Peruvian margin. 1–10: *Perouvianella peruviana* (Steinmann, 1929). 1–2: B forms, 3–7: A forms. Jumasha Formation, Oyón section (central Peru); middle Cenomanian and Ro1 to Co1 sequences. 11–18: *Sellialveolina* cf. *drorimensis* (Reiss, Hamaoui & Ecker, 1964). Cajamarca Formation, Cochaconga section, northern Peru); Ca3 sequence. 19–22: *Sellialveolina* sp., Jumasha Formation, Oyón section (central Peru); middle Cenomanian sequence.

benthonic foraminiferan which not only survived the Cenomanian–Turonian boundary events, but did so without visible modifications.

6. Comparisons and discussion

This sedimentological analysis led us to identify various geological events and relative sea level changes in the late Cenomanian–early Turonian beds of Peru. In order to determine their regional or global extent, and thus their tectonic or eustatic origin, it is necessary to compare them with the events recorded in other Andean basins, and with published eustatic sea level charts.

Comparisons with other Andean basins

The Colombian–Venezuelan Basin: In this area (Figure 1), the late Cenomanian timespan is locally marked by a major sedimentary discontinuity which separates Cenomanian platform limestones (Cogollo, Salto Formations) from monotonous pelagic anoxic shales and limestones (La Luna, Villeta Formations). Towards the northwest, the base of the anoxic deposits is dated as Cenomanian (Julivert, 1968; Martínez & Hernandez, 1992) and no sedimentary or lithologic gap is observed between the Cenomanian and Turonian beds (Barrio & Coffield, 1992). To the southeast, the base of the anoxic deposits is Coniacian in age (Julivert, 1968). Farther southeast, marine glauconitic sandstones (Escandalosa Formation) lap onto Early Cretaceous or older rocks, and gradually pass upwards into marls and limestones (Guayacán Member) locally dated as late Turonian (Macellari, 1988; Martínez & Hernandez, 1992). A major maximum flooding is thought to occur during Turonian times (Macellari, 1988). However, neither an important stratigraphic gap nor a tectonic event of late Cenomanian to early Turonian age has been reported as far.

Other regions of the Central Andean Basin: In the eastern part of the Central Andean Basin, late Cenomanian to early Turonian deposits are generally absent (Bristow & Hoffstetter, 1977; Müller & Aliaga, 1981; Benitez, 1991). Towards the east and northeast, the sedimentary gap may encompass the entire mid-Cenomanian–early Coniacian interval. This major discontinuity separates mainly deltaic sandstones (T sandstones of Ecuador, Agua Caliente Formation of Peru) from overlying Turonian marine marls and limestones, commonly underlain by transgressive glauconitic sandstones (middle Napo and lower Chonta Formations). As a consequence, anoxic marine deposits of latest Cenomanian to earliest Turonian age are virtually unknown, and are locally replaced by carbonaceous transgressive deposits. Although of increasing importance toward the east and northeast, this widespread sedimentary gap is probably present in the western trough where the Co1 is often lacking (Cajamarca section).

In the Andes of Bolivia, *Neolobites* cf. *vibrayeanus* (= *kummeli*) was found in a 10 to 20 m-thick sequence of marine limestones (Miraflores Formation; Branisa, 1968). The top of the Miraflores Formation is most commonly lacking due either to non-deposition or to subsequent erosion (Sempere, in press). In some places, however, the ammonite-bearing beds are overlain by a thin marine sequence of probable late Cenomanian age capped by a hardground. This is overlain in turn by a few metres of intertidal micritic limestones, in which the Turonian Co2-Ca1 and Ca2-Ca3 sequences are recognizable (Jaillard & Sempere, 1991). If correctly interpreted, the hardground would represent a sedimentary gap of late Cenomanian–earliest Turonian age.

The Argentine and Chilean basins: In the southern sedimentary basins, the Cenomanian–Turonian evolution is dominated by the occurrence of a major mid-Cenomanian tectonic phase that produced deformations, sedimentary gaps, or subsidence according to region (Macellari, 1988; Riccardi, 1988).

In the Neuquén Basin (Figure 1), the major mid-Cenomanian unconformity separates underlying fluvial or lacustrine deposits from continental red beds (Macellari, 1988). This tectonic event produced a significant sedimentary gap that encompasses either the late Cenomanian to early Coniacian timespan (Riccardi, 1988), or a minor hiatus (Macellari, 1988). The overlying red beds overlap older rocks towards the east or southeast and comprise three poorly dated fining-upward sequences (Macellari, 1988).

In Patagonia (Figure 1), mid-Cenomanian compressive deformation resulted in the closure of the western back-arc basin and triggered the subsidence of the Magallanes Trough, interpreted as a foreland basin (Biddle *et al.*, 1986). In its western part, an important sedimentary hiatus of late Cenomanian to early Coniacian age is observed (Macellari, 1988). In the eastern part, after a mid-Cenomanian hiatus, the late Cenomanian–Turonian timespan is represented by locally glauconitic claystones and shales (Mid-Inoceramus shales), exhibiting neither a significant discontinuity nor a lithologic break (Biddle *et al.*, 1986).

Comparisons with eustatic sea level charts (Figure 8)

The first major flooding period (Ro1) is characterized by the occurrence of *Neolobites*, and overlies a major sequence boundary of late mid-Cenomanian age. The latter could be correlated with the 94 Ma discontinuity reported by Haq *et al.* (1987), while the former should correspond to the 93.5 Ma condensed sections of the chart of Haq *et al.* (1987).

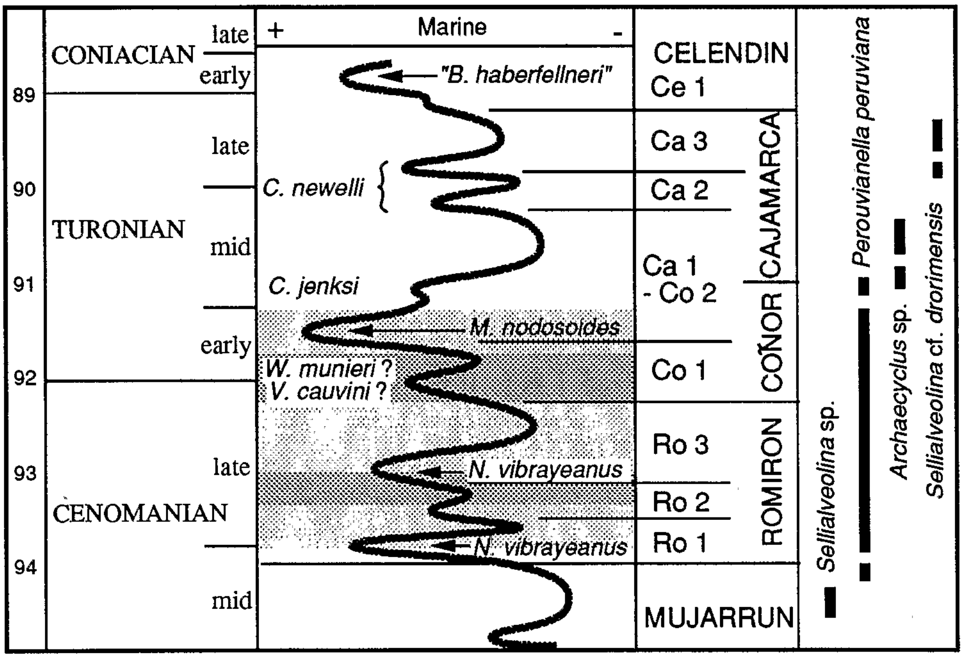

Figure 8. General eustatic model for late Cenomanian–Turonian sedimentation on the Peruvian margin, and stratigraphic range of the benthonic foraminifers mentioned.

The Ro2 and Ro3 minor flooding surfaces also contain *Neolobites*. No equivalents have been found in the eustatic charts (Haq *et al.*, 1987).

The Co1 maximum flooding occurred before the first appearance of *M. nodosoides* (Figure 8). The possible occurrence of *V. cauvini?*, *W. munieri?* and *Thomasites* suggests a latest Cenomanian to earliest Turonian age, perhaps corresponding to the *Thomasites* and *Choffaticeras*-bearing condensed interval mentioned by Robaszinsky *et al.* (1990) at about 91.9 Ma. In most of the Peruvian sections, evidence of emergence is present at the top of nearly all of the latest middle to early late Cenomanian parasequences, whereas no tidal deposits are known in the early Turonian sequences except for Co1 in Tembladera. Therefore, the depth of deposition abruptly increased between Co1 and Co2, very close to the Cenomanian–Turonian boundary, which is in good agreement with the proposed correlations.

The major Co2 maximum flooding is marked by the occurrence of *M. nodosoides* and corresponds to the well-known early Turonian transgression maximum (Hancock & Kaufmann, 1979). It correlates with the condensed intervals indicated around 91.5 Ma by Haq *et al.* (1987) (Figure 8). The subsequent minor, *Coilopoceras jenksi*-bearing flooding period follows the disappearance of *M. nodosoides*, and is therefore of early middle Turonian age.

The two marl-layers with *C. newelli* (Ca2 and Ca3) apparently correlate with the two widely reported mid-Turonian flooding surfaces at 90.75 and 90.25 Ma respectively (Haq *et al.*, 1987). However, *C. newelli* indicates the late Turonian. In Tunisia, the *Coilopoceras*-bearing condensed sections are of late middle Turonian and late Turonian age (90.25 and about 89.5 Ma, Robaszinski *et al.*, 1990). Hence, unless *C. newelli* appears in the middle Turonian in Peru, the available stratigraphic data are more consistent with the interpretation of the Tunisian section.

The overlying "*B. haberfellneri*"-bearing marls (Ce1, Figure 8) correlate with the well-known early Coniacian maximum flooding (89 Ma, Haq *et al.*, 1987; Robaszinski *et al.*, 1990).

Late Cenomanian–early Turonian dark deposits are observed in all of the studied sections. However, they are very bituminous only in the carbonate platform deposits of central Peru (Oyón). In most of the sections, dark colours seem to be restricted to the highstand systems tracts of the Ro2 to Co2 sequences, the anoxia manifestations vanishing before the *M. nodosoides*-maximum flooding. If the dark colour is accepted as a criterion for anoxia, anoxic maxima seem to occur in the lower part of the Ro3 and between Co1 and Co2, respectively. In some cases, however, restricted conditions can be explained by the local palaeogeographic setting or by peculiar shallow-water environments (Rentema). The high content of organic matter leads us to correlate these deposits with the global anoxic event of the Cenomanian–Turonian boundary.

Discussion

The latest Cenomanian–earliest Turonian deposits of Peru exhibit characteristics intermediate between those of the Caribbean system, dominated by a widespread anoxia and a major eustatic marine transgression, and of the southern region, dominated by tectonic events and sedimentary gaps.

As in the Colombian–Venezuelan Basin, the late Cenomanian–early Turonian deposits of Peru express a general transgressive trend. However, the existence of significant stratigraphic gaps in the eastern part of the Central Andean Basin suggests that an important, though short-lived, relative sea level drop occurred near the Cenomanian–Turonian boundary, thus accounting for the lack of coeval anoxic deposits in most of this area. Moreover, it supports the hypothesis of the local presence of more limited hiatuses in the western, studied area (Cajamarca area).

Although the relative sea level rise caused the carbonate shelf to be drowned in northern Peru, this was not the case in central and southern Peru where carbonate shelf sedimentation appears to have kept pace with sea level through the Cenomanian–Turonian boundary interval. Coeval organic-rich deposits are observed only in the external and more open marine parts of the basin (central and northern Peru) where important sedimentary gaps did not occur. Anoxia seems to have been less dramatic than in the Colombian–Venezuelan Basin, since it did not result in the deposition of bituminous shales. This may be owing to the steep topography of the Andean margin, leaving it wide open to the Pacific Ocean and thus exposed to both upwellings and oceanic currents.

The exceptional persistence of some large benthonic foraminifera species through the Cenomanian–Turonian boundary could be related to the continuity of the carbonate shelf sedimentation and the existence of less drastic anoxic conditions.

Although synsedimentary deformation has not been reported as yet, the occurrence of tectonic movements is suggested by local variations in the subsidence rates. As an example, the late Cenomanian deposits of the Cajamarca section are very thin, whereas they are very thick at Rentema. Conversely, the Turonian limestones of Cajamarca are much thicker than those of Rentema (Figures 3, 4). In the same way, tectonic movements may have magnified or exaggerated the sedimentary gaps or erosion observed in some western sections. Although they can account for part of the relative sea level changes observed in the eastern zones, they appear to be much less important than those observed in the southern Andean basins.

The major flooding events (Ro1, Co2, Ce1) and, in spite of some stratigraphic uncertainties, the Turonian sequence succession exhibit good correlations with the available eustatic charts. In contrast, the late Cenomanian to earliest Turonian sequences (Ro2 to Co1) do not display clear correlations with eustatic variations, thus supporting the interpretation of a possible tectonic origin for these events. However, further palaeontological and sedimentological studies are necessary in order to refine the age and evolution of these deposits.

7. Conclusions

In a first approximation, the late middle Cenomanian to late Turonian deposits of Peru can be interpreted as one depositional megasequence. The detrital Romirón marls would constitute the transgressive systems tract; the fossiliferous Coñor marls would represent the maximum flooding; and the Cajamarca shelf limestones the highstand systems tract (and incipient transgressive systems tract). Three sequences (Ro1 to 3) can be recognized in the latest middle to early late Cenomanian interval, and two or three sequences (Co1 and Co2-3) in the latest Cenomanian to early Turonian timespan. The overlying Cajamarca Formation is made of three well developed depositional sequences of middle to late Turonian age. Depositional environments remain shallow during the late Cenomanian, especially during the Ro3 highstand systems tract. As a consequence, the widespread absence of the Co1 sequence of latest Cenomanian to earliest Turonian age could be ascribed to a period of non-deposition because of an important relative sea level drop. The Cenomanian–Turonian boundary seems to lie within the Co1 sequence.

Comparisons with published charts show that most of the discontinuities and depositional sequences recognized in Peru coincide with global eustatic events, especially the Ro1 (*Neolobites*), Co2 (*M. nodosoides*) and Ce1 ("*B. haberfellneri*") maximum floodings. However, a tectonic contribution to the relative sea level variations during late Cenomanian times is suggested by variations in the subsidence rate, frequent erosion, and comparisons with southern Andean basins.

Dark deposits and restricted or anoxic environments characterize the Ro1 to Co1 sequences and seem to peak during the Ro3 and Co1 sequences. These anoxic deposits therefore coincide with the well-known anoxic event of the Cenomanian–Turonian boundary. However, anoxia seems to be much less pronounced than in the Caribbean or Atlantic domain, perhaps because the steep topography of such active margins exposed them to upwelling and oceanic circulation. This may have allowed shelf limestone deposition to persist locally during the Cenomanian–Turonian boundary interval on the Peruvian margin.

In northern Peru, the late Turonian deposits contain *Sellialveolina* cf. *drorimensis*, a species known from Cenomanian deposits elsewhere. In central Peru, *Perouvianella peruviana* seems to be present throughout the late Cenomanian to early Turonian deposits. Therefore, Peru would be an exceptional area where large benthonic foraminifera like *P. peruviana* do not disappear during the Cenomanian–Turonian boundary crisis.

Acknowledgements

The French Institute of Andean Studies (IFEA, Lima), the French Institute of Scientific Research for Development through Cooperation (Orstom, Paris) and the Dolomieu Institute (Grenoble) supported field and laboratory work. We are indebted to M. Caron and W. J. Kennedy for palaeontological determinations, to K. Biddle and A. von Hillebrandt for constructive reviews, and to P. Cooper for significantly improving the English text.

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