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Cretaceous to early Paleogene tectonic evolution of the northern Central Andes (0–18°S) and its relations to geodynamics

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(Text continued on inside back cover)

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Abstract

The tectonic phases, subsidence patterns and location of the magmatic arc along the Peruvian margin during Late Cretaceous and Paleogene times are compared with the main geodynamic parameters: absolute plate motion; convergence velocity and direction; age of the subducted slab; and accretional events for the same periods. During the Late Cretaceous, long-termed compression seems to be controlled by the absolute trenchward motion of the overriding plate, and, to a minor extent, by the young age of the subducted lithosphere. Short-lived contractional or extensional phases are mainly linked to the acceleration or deceleration of the convergence between the oceanic and continental plates, and probably to changes in the convergence direction. Periods of high and low convergence rates coincide with increased and decreased subsidence rates along the margin, respectively, and seem to be independent of compressional–tensional regimes. During the Paleogene, in addition to the mentioned processes, the eastward shift of the magmatic belt and subsidence in the forearc zone are interpreted as the result of the subduction erosion of the margin. This process seems to be related to the decrease of the dip of the Benioff zone, expressed by the drastic widening of the magmatic arc.

1. Introduction

Most classical geodynamic models for the origin of the tectonic phases in continental active margins are based on the observation and comparison of various present-day active margins (Uyeda and Kanamori, 1979; Scholl et al., 1980; Uyeda, 1982; Cross and Pilger, 1982; Jarrard, 1986), or through physical modelling (Bott et al., 1989; Whittaker et al., 1992; Cloos, 1993). Only few ones have been elaborated through the study of active margin evolution through a long period of time. The aim of this paper is to present some geological constraints and to propose new hypotheses for the origin and nature of the tectonic phases of continental active margins through the study of the sedimentary, tectonic and magmatic evolution of the Ecuadorian and Peruvian Andes between 0 and 18°S, from early Albian to Late Eocene times.

During most of the Cretaceous, the Peruvian margin comprised from west to east (Fig. 1; Benavides, 1956; Mégard, 1984; Jaillard, 1994): (1) a coastal zone, marked by the development of a magmatic arc, mostly active from Albian times onwards; (2) a subsident and mobile Western Trough where thick marine deposits accumulated; (3) an Axial Threshold with reduced sedimentation and subsidence; and (4)

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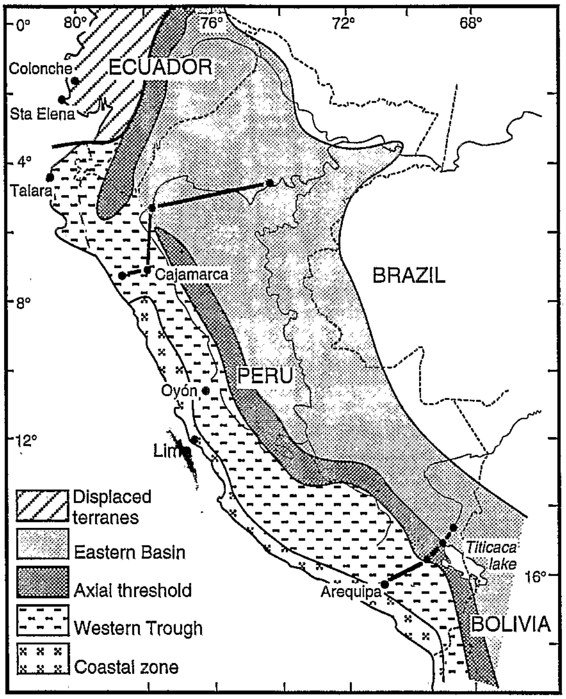

Fig. 1. Paleogeographic sketch of the Peruvian–Ecuadorian margin during Cretaceous times. Heavy lines represents the profiles of Fig. 4. Sections of Figs. 3 and 5 are also shown.

an Eastern, weakly subsident, stable basin which received mixed marine and continental sediments. In western Ecuador, oceanic island arcs were accreted during Paleogene times (Fig. 1; Bourgois et al., 1990).

2. Evolution of the Central Andes from Late Jurassic to Oligocene

The Cretaceous–Paleogene evolution of the Central Andes can be divided into various periods (Jaillard, 1994; Sempéré, 1994, and references therein). The Cretaceous evolution is in great part controlled by Late Jurassic tectonic events.

2.1. Tithonian–Aptian

Between 145 and 130 Ma (Late Jurassic–Berriasian), mainly extensional tectonic events occurred and were roughly coeval with the activity of a volcanic arc along the Peruvian margin (Atherton et al., 1985). These events provoked the sedimentation of widespread, often disconformable clastic deposits (Vicente, 1981) and the uplift and emergence of large areas of southern Peru (Batty and Jaillard, 1989). In northern Peru, an extensional tectonic phase of Tithonian age caused the creation of a deep sedimentary basin (Chicama basin; Fig. 2; Jaillard and Jacay, 1989) that underwent about 2 km of initial subsidence, allowing the accumulation of as much as 2500 m of late Tithonian marine sediments, and controlling the whole Cretaceous subsidence history of this area (Fig. 4).

During Early Cretaceous times, east-deriving fluvio-deltaic sandstones were laid down throughout the Central Andean domain (Fig. 2; Benavides, 1956; Moulin, 1989; Batty and Jaillard, 1989). Only the Lima area was marked by the development of an Early Cretaceous carbonate platform. Magmatic and tectonic activities are virtually lacking (Moulin, 1989; Soler and Bonhomme, 1990). During this period (130–110 Ma), an important thermal subsidence of about 1 km occurred in the newly created basin, whereas the virtually unstretched areas recorded a slow subsidence rate (≤ 350 m) (Fig. 4).

2.2. Early Albian–Turonian (Mochica period)

During latest Aptian to early Albian times, the Peruvian margin underwent an extensional tectonic activity (Jaillard, 1987), associated with an incipient calc-alkaline volcanic arc and scattered alkaline volcanic outflows in the back-arc (Soler, 1989, 1991). The Albian period is then marked by a marine transgression that overwhelmed the whole domain (Kummel, 1948; Benavides, 1956; Mégard, 1978) and resulted in regional on-lap of fluvio-deltaic deposits onto the eastern border of the Andean Basin. Then a regression occurred that culminated in late Albian and/or early Cenomanian times with the progradation of deltaic sandstones originating from the east (Figs. 2 and 3; Jaillard, 1987, 1994). The westernmost part of the margin recorded the intense volcanic activity of a magmatic arc (Casma Group; Atherton et al., 1985; Soler, 1991), the beginning of upper-crustal magmatic intrusions (Coastal Batholith; Beckinsale et al., 1985; Soler, 1991), and alternating extensional and contractional tectonic deformation

(Cobbing et al., 1981). Volcanic activity ceased by late Albian–early Cenomanian times, as the western part of the margin was deformed by a first major contractional event (Mochica phase; Fig. 2; Mégard, 1984). This was probably associated with a strong dextral wrenching component (Bussel and Pitcher, 1985), and is recorded by extensional synsedimentary tectonic features in the whole western domain (Jaillard, 1994).

Between middle Cenomanian and Turonian times, major marine transgressions deposited widespread shelf carbonates that recorded the main eustatic discontinuities (Fig. 3). During this period, the location of the volcanic front (i.e., the trenchward boundary of the volcanic activity) remained unchanged (Soler and Bonhomme, 1990). From 110 to 90 Ma (late Aptian–Turonian), the subsidence rate increased in the parts of the Western Trough floored by stretched continental crust (Fig. 4). In eastern Peru, no significant changes are observed except in the easternmost areas and in eastern Ecuador, where an increase of tectonic subsidence occurred at 110 Ma (Berrones, 1992; Contreras, 1996).

2.3. Coniacian–early Late Paleocene (Peruvian period)

Along the entire northern Central Andean margin, early Coniacian times were marked by the beginning of fine-grained detrital, mainly argillaceous sedimentation (Figs. 2 and 3; Tschopp, 1953; Benavides, 1956; Pardo and Zuñiga, 1976; Vicente, 1981; Jaillard, 1994), which rests locally disconformably upon the Turonian limestones (Sempéré, 1994), and is probably related to the erosion of locally tectonized coastal areas (Jaillard, 1994; Sempéré, 1994). After a period of relative tectonic quiescence, a major contractional phase occurred during late (?) Campanian times (Gayet et al., 1991; Jaillard et al., 1993). This phase is responsible for a 300-km-long overthrust in southwestern Peru, with a few tens of kilometres of minimum northeastward displacement (Vicente, 1989), for a marine transgression in northwestern Peru and southwestern Ecuador (González, 1976; Séranne, 1987; Jaillard et al., 1996), and the slight eastward shift of the magmatic arc (Coastal Batholith) with respect to its previous location (Fig. 2; Soler

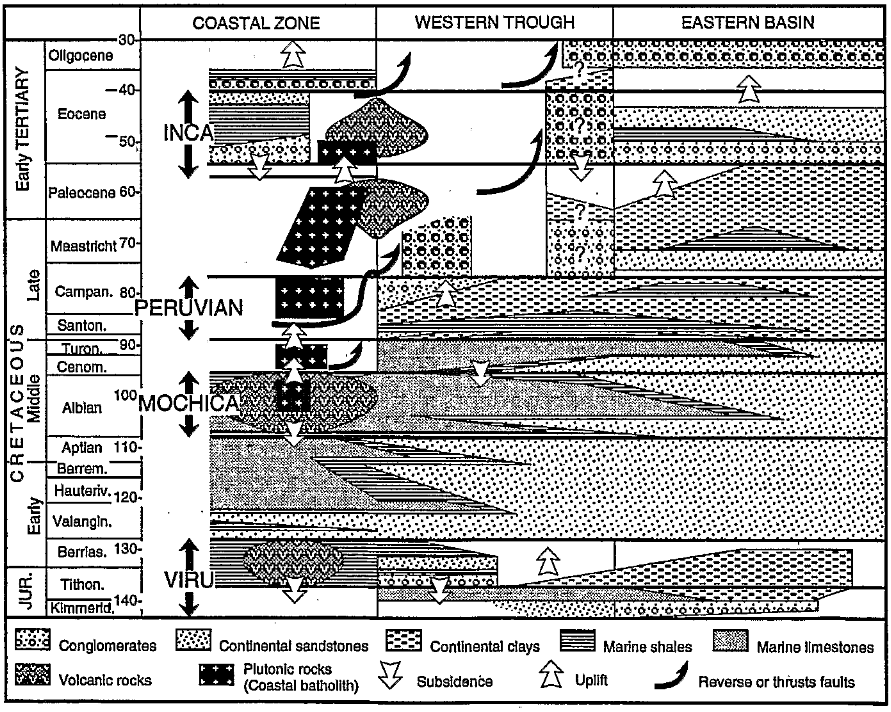

Fig. 2. Sketch of the sedimentary, tectonic and magmatic evolution of the Peruvian margin during Cretaceous and Paleogene times.

and Bonhomme, 1990). Farther east, this tectonic phase caused the deposition of widespread sandstones in the Axial Treshold and the Eastern domain (Koch and Blissenbach, 1962; Pardo and Zuñiga, 1976; Jaillard et al., 1993). In the Cuzco area, the Late Cretaceous age of thick series of Red Beds expressing the creation of rapidly subsiding troughs (Noblet et al., 1987; López and Córdova, 1988) is currently questioned. A new period of relative tectonic quiescence occurred during Maastrichtian times, which is characterized by widespread, short-lived marine transgressions (Gayet et al., 1991; Jaillard et al., 1993). In Maastrichtian and Paleocene times, large volumes of volcanic and plutonic rocks were emplaced all along the Peruvian margin (Fig. 2; Laughlin et al., 1968; Beckinsale et al., 1985; Clark et al., 1990).

Between 90–80 and 55 Ma (Senonian–Late Paleocene), two situations occurred as regards subsidence. In northern Peru where deformation was relatively weak, the subsidence rate decreased significantly, resulting in important sedimentary gaps (Fig. 4). In southern Peru, where the deformation was stronger (Vicente, 1989; Jaillard, 1994) the subsidence rate remained unchanged or slightly increased. In Bolivia, the strong increase in subsidence is interpreted as the result of lithospheric flexure (foreland-type subsidence) related to the incipient Andean shortening (Figs. 3 and 4; Sempéré, 1994).

2.4. Late Paleocene–Late Eocene (Incaic period)

In the Eastern basin, from Bolivia to northern Peru, widespread unconformities are observed between fine-grained Paleocene and coarse-grained Eocene continental deposits (Incaic 1 phase; Fig. 2; Faucher and Savoyat, 1973; Marocco et al., 1987; Noble et al., 1990; Naeser et al., 1991; Gayet et al., 1991). The latter are overlain or associated with marine to lacustrine deposits of Early to Middle Eocene age (Naeser et al., 1991; Benitez et al., 1993). The Late Eocene Incaic 2 shortening phase caused extensive folding and reverse faulting in the former Western Trough, and the formation of a fold and thrust belt along the entire Western Trough–Axial Threshold boundary (Dalmayrac et al., 1980;

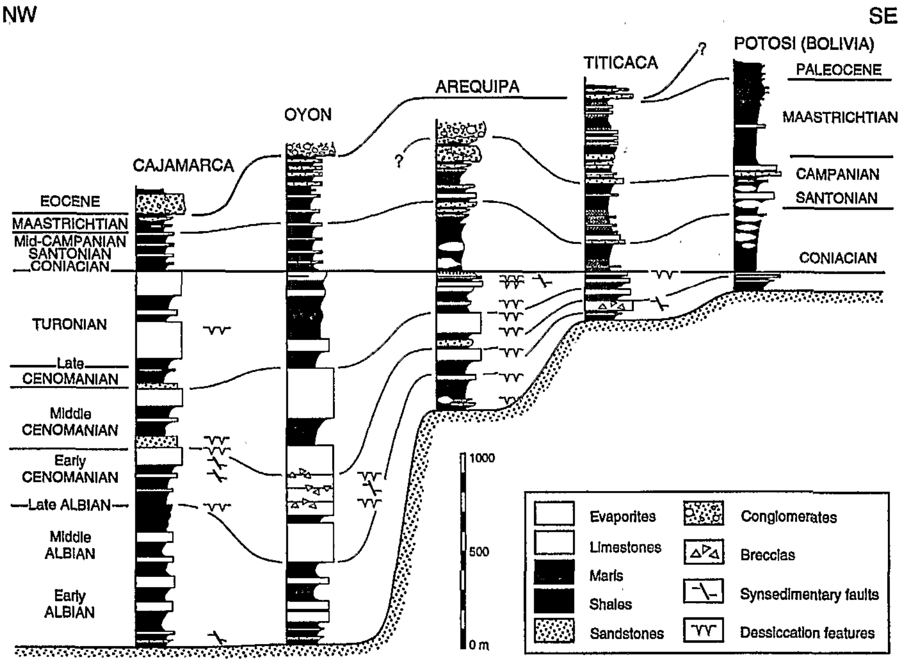

Fig. 3. Representative sections through the Peruvian and Bolivian continental margin, showing the sedimentary evolution between Albian and Eocene times (location on Fig. 1). Data are from Jaillard (1987) for Cajamarca and Oyón, Jaillard (1994) for Arequipa, Jaillard et al. (1993) for Titicaca and Sempéré (1994) for Potosi.

Mégard, 1984; Mourier, 1988). In nearly all the Central Andean sedimentary basins, Late Eocene to Early Oligocene times are marked by a widespread sedimentary hiatus (Marocco et al., 1995).

In the arc zone, sharp plutonic gaps related to contractional deformation are recorded during Late Paleocene and Middle Eocene times (Fig. 2; Soler and Bonhomme, 1990). The major Late Eocene shortening phase is marked by a significant eastward shift of the magmatic front, and by the dramatic widening of the magmatic arc, which reached the western edge of the Eastern basin (present-day Eastern Cordillera).

The accretion of island arcs in southwestern Ecuador during Late Paleocene–earliest Eocene times was followed in southwestern Ecuador and northern

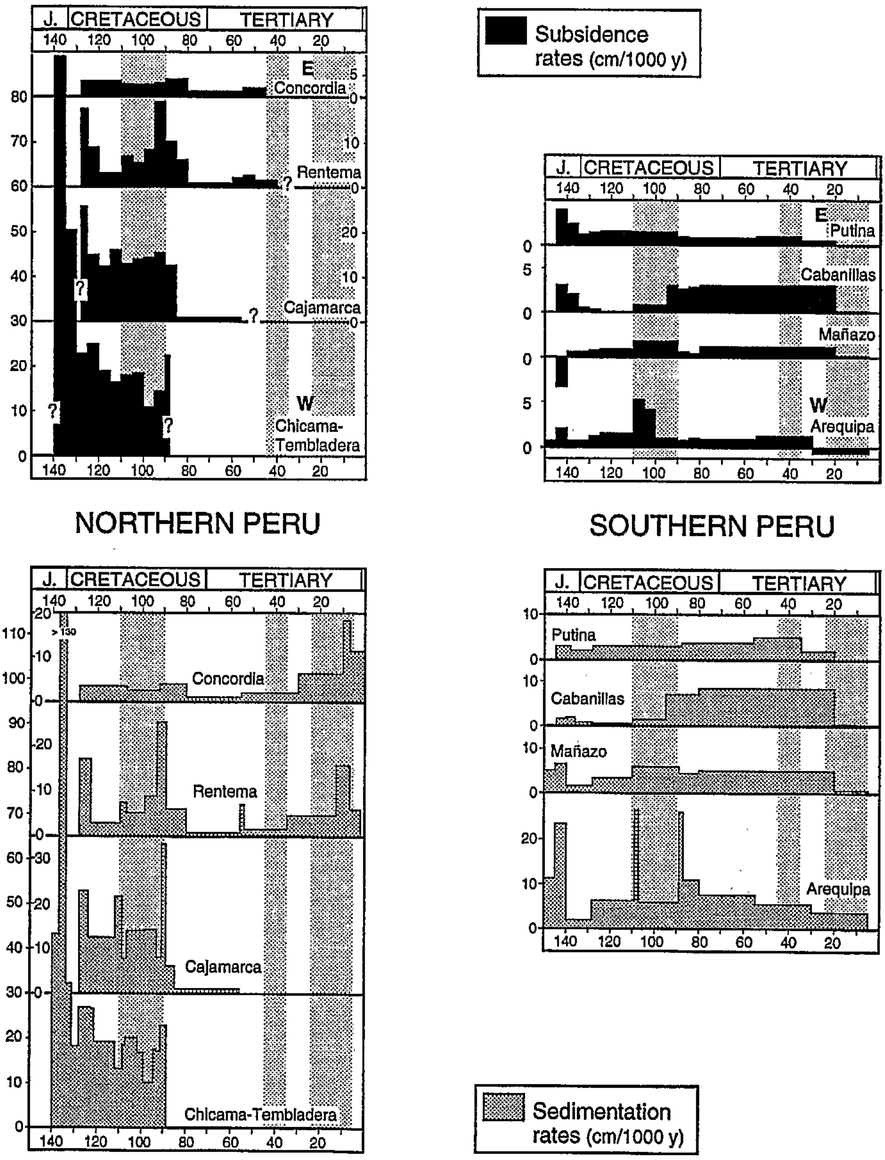

Fig. 4. Decompacted subsidence and sedimentation rates along two profiles across the Peruvian margin (location on Fig. 1).

Peru by the deposition of latest Paleocene or Early Eocene unconformable coarse-grained marine conglomerates, and/or by a sedimentary gap of Early Eocene age (Figs. 2 and 5; González, 1976; Séranne, 1987; Jaillard et al., 1995). In most of the forearc regions, a tectonic subsidence of several hundreds of metres of early Middle Eocene age provoked the deposition of shallowing-upward marine sequences resting unconformably on Paleocene, Cretaceous or older rocks (Evans and Whittaker, 1982; Macharé et al., 1986; Ballesteros et al., 1988; Jaillard et al., 1995). In the whole coastal Ecuador and northwestern Peru, this period ended up with the deposition of continental to shorezone sandstones and conglomerates of late Middle to early Late Eocene age evidencing a tectonic event (Fig. 5; González, 1976; Jaillard et al., 1995). The latter (Incaic 2 phase) coincides with the blocking of an oceanic-floored island arc

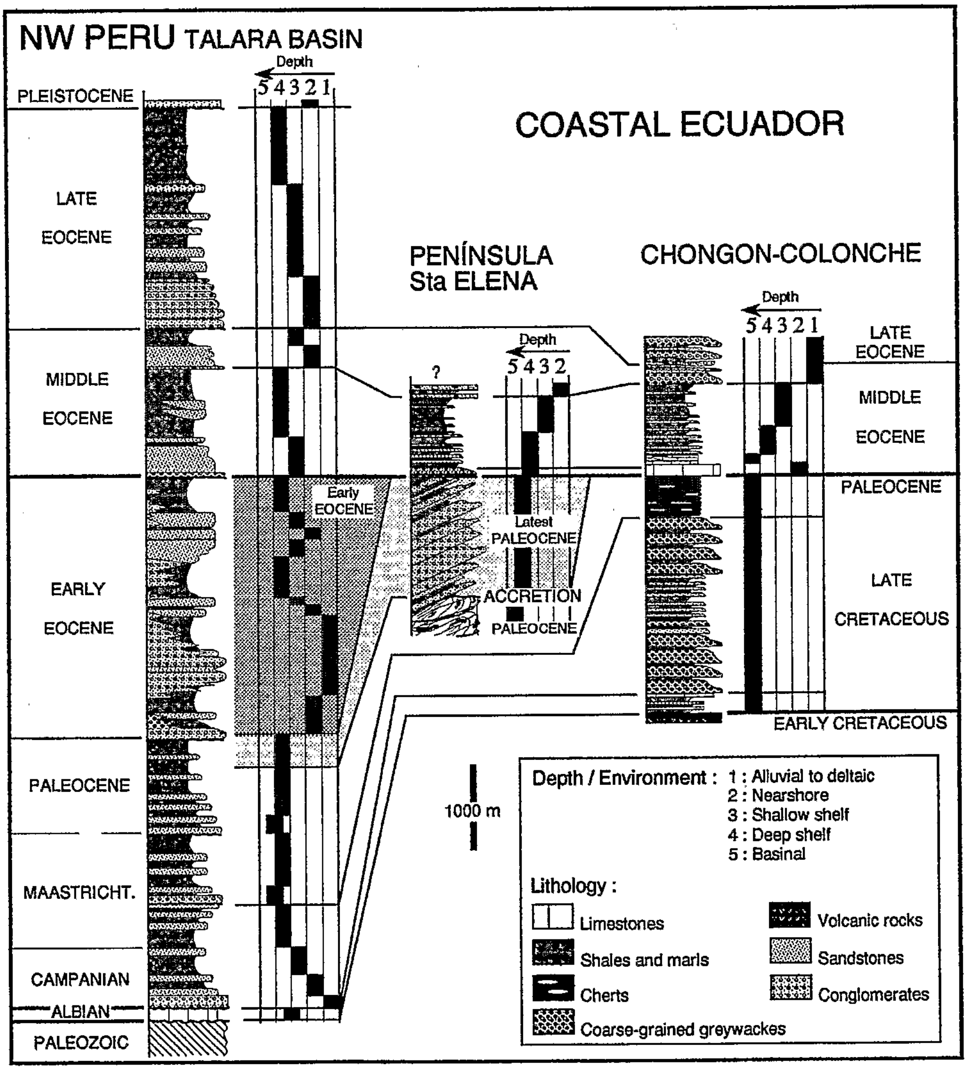

Fig. 5. Sedimentary evolution of the forearc zones of northwestern Peru and southern Ecuador during Late Cretaceous to Eocene times (location on Fig. 1). Data are from González (1976) for Talara and Jaillard et al. (1995) for coastal Ecuador.

against the continental Andean margin (Bourgois et al., 1990).

3. Relations to geodynamic factors

Geodynamic reconstructions are poorly constrained for the Late Cretaceous period (Pardo-Casas and Molnar, 1987), especially as regards the plate kinematic reorganizations, subduction of ridges, dip of the subducting slab and direction of convergence. Therefore, these factors will not be discussed in this paper. However, quantitative approximation of some parameters, such as the convergence velocity (Soler and Bonhomme, 1990) deduced from the global spreading rates (Larson, 1991), the absolute motion of the South American plate driven by the opening and ridge activity of the South Atlantic Ocean (e.g., Nürnberg and Müller, 1991) and the age of the oceanic slab while subducted, calculated by a step by step method proposed by Soler et al. (1989) and Soler (1991), allow us to analyze them in relation to the early tectonic evolution of the northern Central Andean margin.

3.1. Age of the subducted slab

Classical models assume that the subduction of a young, buoyant oceanic lithosphere induces a contractional strain in the overriding continental plate (Molnar and Atwater, 1978; Cross and Pilger, 1982; Sacks, 1983). After Soler et al. (1989), the beginning of the contractional period (Albian) roughly coincides with the rejuvenation of the oceanic plate subducting at that time (Fig. 6). However, the Late Cretaceous and Paleogene shortening phases occurred during a continuous increase in the relative age of the subducted slab. Therefore, the lithospheric age of the subducted slab could contribute to the appearance of a long-termed contractional regime, but cannot account for short-termed shortening phases.

3.2. Absolute trenchward motion of the overriding plate

As noted by many authors (e.g., Frutos, 1981; Bourgois and Janjou, 1981; Jarrard, 1986; Soler and Bonhomme, 1990), the opening of the South Atlantic

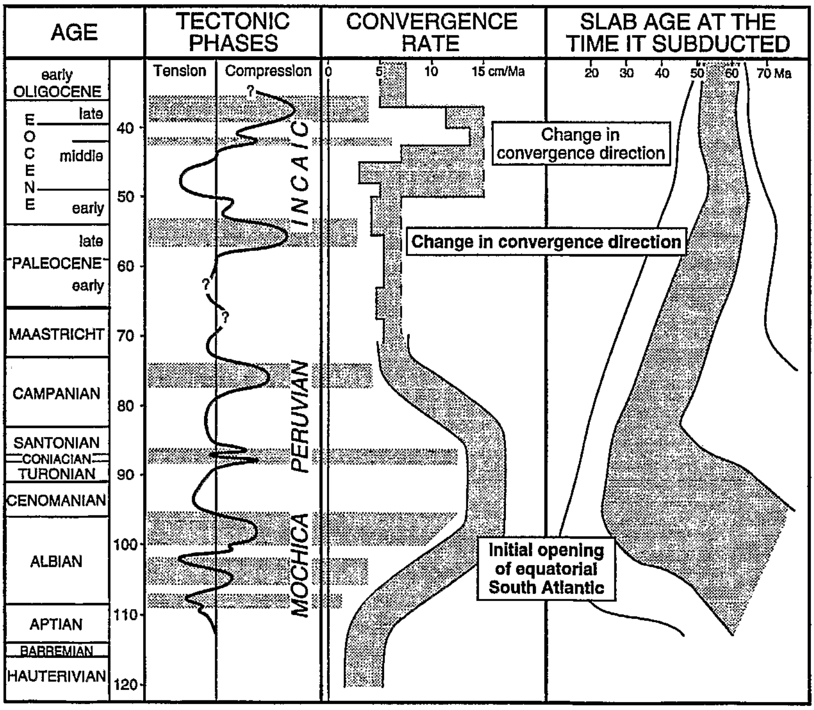

Fig. 6. Comparison of the tectonic evolution of the Peruvian margin with the convergence rate and the age of the subducted slab during the Cretaceous and Paleogene. Convergence rate after Soler and Bonhomme (1990); age of the subducted slab after Soler et al. (1989).

ocean at the equatorial latitudes which provoked the beginning of the westward shift of the South American plate during Albian times, roughly coincides with the initiation of the contractional deformations along the Peruvian–Ecuadorian margin (Fig. 6). Thus, this parameter seems to control the long-termed contractional regime of the continental active margin.

As emphasized by Sébrier and Soler (1991) for the late Tertiary Andean contractional phases (their generalized short-lived compressional events), during the tectonically "quiet" periods only weak shortening occurs in the retroarc foreland of the Andes, and then, most of the westward drift of the South American plate should be accommodated by absolute westward overriding of the continental plate over a retreating Nazca slab. The amount of tectonic shortening observed during the contractional phases implies that virtually all the westward drift of the South American plate is accommodated by the shortening and that the western continental margin of the South American plate is virtually motionless in an absolute reference frame (i.e., slab retreat ceases) during these episodes. This recurrent cessation of slab retreat, the mechanical origins of which are unclear, might be one of the driving mechanisms of the short-lived contractional tectonic event.

3.3. Collision of continental or oceanic obstacles

It has been proposed that the arrival in the trench of oceanic or continental obstacles (aseismic ridges, seamounts, continental microplates) will lead to blocking of subduction, contractional deformation of the continental margin and plate reorganization (Scholl et al., 1980; Cross and Pilger, 1982; Ben-Avraham and Nur, 1987).

According to Cloos (1993), only continental blocks and oceanic island arcs with a crust of more than 15–20 km thick, or basaltic plateau with crustal thickness of more than 30 km will cause jamming in the subduction zone. The current subduction of the 15 km thick inactive Nazca ridge results in extensive subduction erosion of the forearc, and local uplift of ca. 900 m associated with only moderate horizontal compressional stress (Couch and Whitsett, 1981; Macharé and Ortlieb, 1992). Thus, the arrival of moderately high obstacles in the trench seems to have a moderate deformational effect on the upper active margin. On the other hand, the accretion of oceanic island arc terranes on Coastal Ecuador (Late Paleocene–earliest Eocene and Late Eocene) are coeval with the contractional phases observed in Bolivia, southern Peru and northern Peru, where no collisions are known to have occurred. Thus, in this case, it seems that accretions or collisions of terranes cannot be the cause of regional contractional phases. In the studied area, the fact that contraction took place in non-accretionary settings at the same time as accretions occurred suggests that the accretion events and the coeval contractional phases are the consequences of the same global geodynamic mechanism.

3.4. Convergence rate

Following Uyeda and Kanamori (1979), Cross and Pilger (1982) or Pardo-Casas and Molnar (1987), a rapid convergence between the oceanic and continental plates provokes a compressional stress in the latter. After Soler and Bonhomme (1990), periods of high convergence rates along the Peruvian margin occurred in Albian–Campanian and Late Eocene–Early Oligocene times, which coincide roughly with mainly contractional tectonic periods (Fig. 6). However, rather than with the convergence velocity itself, the short-lived tectonic events seem to correlate better with changes in the convergence velocity, whichever their sign: either positive (acceleration) or negative (deceleration). If the reconstruction of Soler and Bonhomme (1990) is correct, accelerations occurred in late Aptian (≈ 110 Ma), late Campanian (≈ 75 Ma), Early to Middle Eocene (≈ 50 Ma) and latest Eocene times (≈ 38 Ma, acceleration), whereas decelerations occurred in late Albian–early Cenomanian (≈ 100–95 Ma), late Santonian (≈ 85 Ma) and late Middle Eocene (≈ 42 Ma, Fig. 6). Except for the late Santonian all these periods coincide with apparently extensional (late Aptian, Early–Middle Eocene boundary) or important contractional tectonic phases. Therefore, short-lived contractional phases as well as extensional tectonic events seem to be mainly controlled by changes in the convergence velocity (Fig. 6).

3.5. Direction of convergence

The geometry of the geodynamic reconstructions are too poorly constrained to allow a valuable discussion for the Late Cretaceous. The Incaic contractional tectonic phases of Late Paleocene (≈ 55–58 Ma) and late Middle Eocene age (43–42 Ma; Mégard, 1984; Jaillard, 1994) coincide with successive clockwise rotation in the direction of convergence (Pilger, 1984; Gordon and Jurdy, 1986; Pardo-Casas and Molnar, 1987; Mayes et al., 1990). These changes in the convergence direction, which caused successive significant increases of the normal convergence rates seem to have the same effects as those assumed for a convergence acceleration.

Moreover, the important changes in the convergence direction from north-northeast to east-northeast by Late Paleocene times (55–58 Ma, Fig. 6) must have induced drastic changes in subduction geometry. The NNE-trending Ecuadorian margin changed from a mainly transform to a chiefly convergent regime. This must have induced the eastward drift and accretion of oceanic island arcs along the Ecuadorian margin and the birth of new subduction zones west of them (Jaillard et al., 1995). The change in the convergence direction of late Middle Eocene age (43–42 Ma) also resulted in a new event of collision of island arcs along the Ecuadorian margin (Bourgois et al., 1990). Thus, changes in the convergence direction not only control the normal convergence rate, but also play a part in the regional subduction pattern that could in turn influence the tectonic regime. Such changes in the convergence direction during the Paleogene can explain the contemporaneity of the contractional events in non-accretionary settings of the Central Andes and the collisions of island arcs.

3.6. Relation convergence rates–subsidence

In northern Peru, periods of slow plate convergence correlate with low subsidence rates [130–110 Ma (?), 80–45 Ma, Figs. 4 and 6]. Conversely, the periods of high convergence velocity are coeval with periods of increased subsidence rate (110 to 90–80 Ma, Figs. 4 and 6). This cannot be explained by increased subduction erosion of the deep continental margin (Von Huene and Scholl, 1991), because this latter model is only proved to account for the subsidence of the external part of the margin, close to the subduction zone, whereas increased subsidence is observed as far as the Eastern domain between 110 and 90–80 Ma (Fig. 4; Contreras, 1996). In contrast, these observations are consistent with the thermal model of Mitrovica et al. (1989), that assumes that a fast convergence provokes an increase of the subsidence rates in the whole continental margin, through mantle convection (Gurnis, 1992; Stern and Holt, 1994). The lack of such correlations in southern Peru (Fig. 4) is most probably due to the fact that contractional tectonic events occurred earlier and were stronger than in northern Peru. There, tectonic uplift of the margin by crustal shortening and thickening, and overload tectonic subsidence of the foreland would have prevailed since Senonian times (Sempéré, 1994).

3.7. Dip of subduction and subduction erosion

The continentward shift of the volcanic front is interpreted classically as a result of the shortening of the continental margin, either by compressive tectonic shortening, or by subduction erosion (Scholl et al., 1980). During Albian and early Late Cretaceous times, the location of the magmatic arc was stable (Fig. 7). Therefore, neither significant shortening nor subduction erosion seem to have occurred at this time. The eastward shift of the magmatic arc in the late Campanian (Fig. 7) can be explained mainly by the poorly constrained tectonic shortening related to the major Peruvian phase. As a consequence, we propose that significant subduction erosion did not take place before at least latest Cretaceous, and possibly Eocene times, as indicated by the relative stability of the magmatic arc location before this period.

In Eocene times, the ongoing eastward shift of the magmatic belt is associated with its abrupt widening (Fig. 7), and by extensional subsidence of the forearc (Fig. 5). The broadening of the magmatic arc has been interpreted as the result of a widening of the melting zone in the asthenospheric wedge linked to a decrease of the dip of the Benioff zone, in turn controlled by the normal convergence velocity (Soler, 1991). The rapid subsidence pulse observed in most of the forearc regions by early Middle Eocene times is too widespread to result from local tectonic events or paleogeographic effects. Since it is associated with the ongoing eastward shift of the magmatic front, we propose that both are related to the subduc-

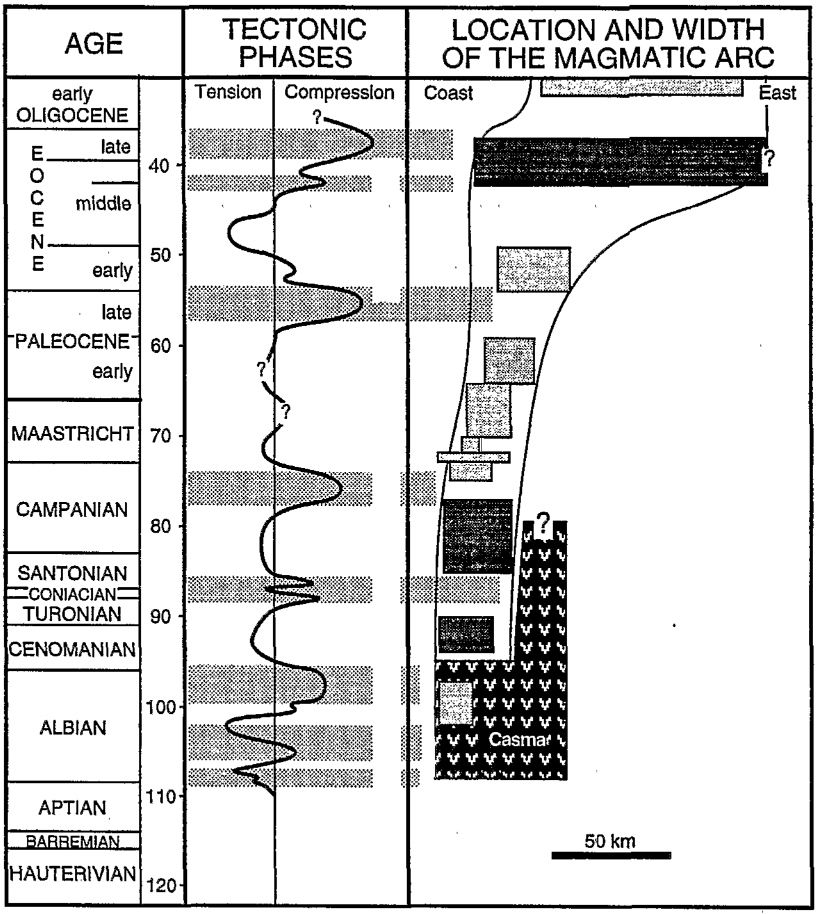

Fig. 7. Tectonic and magmatic evolution of the Peruvian margin during Cretaceous and Paleogene times. Black areas = volcanic rocks of the Casma Group; grey areas = batholith intrusions, darkness of the areas is roughly proportional to the volume of the magmatic products.

tion erosion of the edge of the margin (see Scholl et al., 1980; Von Huene and Lallemand, 1990; Von Huene and Scholl, 1991). Because the widening of the magmatic arc coincides grossly with the assumed initiation of the subduction erosion process, we think that a low-angle subduction plan was a necessary condition for the subduction erosion of the Central Andean margin edge. A low dipping subduction zone would result in increased coupling and shear stress at the contact between the plates, inducing a greater potential of abrasive removal at the base of the overriding plate.

4. Conclusions

The initiation of the westward shift of the South American plate in the Albian coincided with the beginning of contractional deformation in the Peruvian Andes. During the Late Cretaceous, tectonic phases coincided with changes in the convergence rates, either positive or negative. In the relatively weakly deformed areas, subsidence rates depended on the convergence velocity. Thus, during this period, the tectonic evolution and subsidence seem to have been controlled mainly by the absolute plate motion and the relative convergence rate. These mechanisms are then obscured by the superimposition of other tectonic and geodynamic factors during the following period.

Paleogene times are marked, on one hand, by regional contractional deformations and accretions of island arcs in Ecuador (ca. Late Paleocene and ca. Late Eocene). The latter seem to result from changes in the convergence direction, whereas the former are interpreted as related to the coeval changes in the normal convergence velocity. On the other hand, the same period is characterized by the eastward shift and abrupt widening of the magmatic belt, and subsidence of the forearc zones. These are interpreted as the result of a decrease in the dip of the Benioff zone, which induced increased coupling along the Benioff plan and triggered subduction erosion processes.

According to the tectonic evolution of the northern Central Andean continental margin (0–18°S) during Cretaceous–Paleogene times, long-termed compressional regime seems to be controlled by the absolute trenchward motion of the overriding plate, and possibly, by the young age of the subducted lithosphere. Short-lived contractional or extensional tectonic phases seem to be mainly linked to changes (acceleration or decelaration) in the convergence rate between the oceanic and continental plates, and/or to changes in the convergence direction. Periods of high and low convergence rates coincide with increased and decreased subsidence rates in the margin, respectively, and appear to be rather independent of contractional–tensional regimes. A progressive decrease in the dip of the subduction beneath this part of the Andes is thought to cause both the broadening of the magmatic arc and the onset of the subduction erosion of the continental edge, expressed by the subsidence of the forearc zone and the continent-ward shift of the magmatic belt.

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