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Cretaceous tectonics of the Andes

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Kimmeridgian to Paleocene Tectonic and Geodynamic Evolution of the Peruvian (and Ecuadorian) Margin

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Abstract

Three main tectonic periods are recognized between Kimmeridgian and Paleocene times in the Peruvian-Ecuadorian margin.
The "Virú" period comprises a Kimmeridgian event probably equivalent to the Araucan phase of Argentina and Chile, a Tithonian phase related to terrane accretions and collision tectonics along the Ecuadorian margin and to a sudden extension along the north Peruvian margin, and a Berriasian event most probably originated by the incipient South Atlantic rifting.
The "Mochica" period begins with tensional and volcanic precursor events (Late Aptian-earliest Albian). It continues with extensional effusions of coastal, back-arc or arc volcanic centres, which alternate with compressive crises (Early and Middle Albian). It ends with the accretion and deformation (thrusting?) of the Albian volcanic arc or back-arc volcanic system (Late Albian-Early Middle Cenomanian).
The "Peruvian" phase starts with a paleogeographic change probably triggered by the incipient coastal uplift (Turonian-Coniacian boundary), and continues in the Late Coniacian-Early Santonian with the initiation of northeastward overthrusts located at the southwestern boundary of the western Trough. It culminates in the latest Campanian, with the creation of intermontane basins which express the onset of the southwestern thrusts, and of foreland basins related to the onset of new overthrusts located at the northeastern boundary of the western Trough.
An extensional regime was probably dominant during latest Jurassic and Early Cretaceous times, leading to formation of the main sedimentary basins, with an apparent quiescence of the subduction-related volcanic systems. In Late Aptian times, the rapid convergence and rejuvenation of the subducted lithosphere induced a general compressional and/or wrenching regime, triggering the continentalward migration of the trench and the subsequent consumption, deformation and accretion of the volcanic

arc or aborted marginal basin ("Mochica period"). After Cenomanian-Turonian times, the northeastward spread of the compressive strain within the South American plate caused the latter's deformation ("Peruvian period").
The age and velocity of the subducted slab are decisive factors in the general strain regime within the subduction system; whereas variations of the convergence rate at the trench and inherited extensional structures determine the age and location of the short-lived compressional events. These generally correlate with plutonic gaps. Although poorly known, wrenching movements may have been important in the Cretaceous evolution of the Peruvian margin.

Introduction

Aim of this paper

The Andean chain was built up mostly during Tertiary times on a continental margin, as a response to compressional stress induced by the subduction of the Farallón (Nazca) oceanic plate. Nevertheless, during Mesozoic times subduction occurred beneath the central South American margin, but no important chain was formed. One can thus conclude that, though subduction processes are necessary to create an Andean-type chain, they are not sufficient in themselves. In order to recognize the other relevant parameters which act in such an orogeny, it is necessary to study the behaviour of a continental margin submitted to oceanic subduction during a non-orogenic period.
Between Kimmeridgian and Paleocene times the Peruvian-Ecuadorian margin was subjected to the subduction of the Farallón oceanic plate, but tectonic stress, magmatic manifestations, detrital sedimentation and mobility of the substratum were alternately absent, weak or important. The purpose of this synthesis is therefore to describe, to analyse and to interpret when possible the tectonic events recorded by the Peruvian-Ecuadorian margin. Their relationships with geodynamic processes are then examined, and a geodynamic model is proposed.

Methodology

For such a purpose various tools have been used:
Sedimentology studies make it possible to define the environment, evolution and geometry of both depositional sequences and sedimentary basins, to define the source areas and the flooding directions of the detrital supply, and to calculate subsidence curves. The synthesis of the above data, recorded on margin- or basin-scale paleogeographic or isopach maps, can then be used to define the internal shape and deformation of the margin, and to determine the tectonic setting of the sedimentary basins (see Miall, 1984 for review).

Structural analysis makes it posible to determine the direction of paleostress, using various tectonic features.

The analysis of striated synsedimentary faults makes it possible to determine precisely the strain pattern (e.g. Moulin, 1989).

Unstriated synsedimentary faults are assumed to have affected a homogeneous, recently deposited sediment. There, Anderson's principle (1951) has been applied. However, the data are sometimes difficult to interpret, since fracturing may be caused by gravity processes (slumpings and slidings). In this case their orientation is of purely local value, and independent of tectonic strains.

Planes of vertical clastic dykes, in-filled per descensum (opened upward) have been measured, and have been supposed to trend normally to the tensional stress. This can be due either to gravity processes with the dykes then roughly running perpendicular to the paleoslope (Parize et al., 1989), or to tectonic stress, the dykes then trending parallel to the compressional strain (Winslow, 1983). Their interpretation is therefore somewhat difficult.

The slump fold axis and vergences have been measured to try to determine the paleoslope direction.

All measurements have been rotated in order to restore the horizontal stratification, assuming that they were affected by a single folding event, the axis of which was parallel to the observed strata dip. However, in many cases insufficient data, uncertainties in structural identification or measurements, and errors in subsequent rotations may lead to approximate or ambiguous conclusions.

Finally, geochemical and petrological studies on magmatic rocks have led some workers to important tectonic conclusions, which are succinctly mentioned in this paper.

Field work and observations have been made mainly in Peru. However, the tectonic-sedimentary evolution of the Eastern Basin and Cordillera Real of Ecuador will be briefly described together with the northernmost areas of Peru, since they belong to the same paleogeographic units.

Geological Setting

Pre-Cretaceous History and resultant Paleogeography

During the Early Mesozoic, the Peruvian-Ecuadorian margin underwent a complex tectonic and sedimentary evolution (Jaillard et al., 1990).

During the Late Triassic and the Liassic, a thick carbonate shelf developed throughout the margin (Loughmann and Hallam, 1982). Then a Middle to Late Liassic extensional tectonic activity progressively destroyed the shelf. Its destruction was achieved in the Middle Jurassic. At this time, a NNE-trending continental volcanic arc developed in northern Peru and in Ecuador (Mourier et al., 1988a; Aspden et al., 1988), and poorly known subduction-related volcanic rocks overflowed onto the SW-trending coast of southern Peru (Romeuf, 1990). Meanwhile, continental sedimentation and erosions occurred on most of the Peruvian margin, except in southwestern Peru where a turbiditic trough was formed and filled (Vicente et al., 1982).

The Late Liassic and Mid-Jurassic tectonic events resulted in a contrasting paleogeographic pattern, which was later modified during latest Jurassic and earliest Cretaceous times. In this paper we shall describe the tectonic events according to the following paleogeographic zones, from West to East (Figure 1):

- The Coastal Zone included a coastal Cordillera and coastal Troughs. The Coastal Cordillera presently consists of mainly Paleozoic and older rocks, because Tertiary erosion removed most of the Mesozoic rocks. It now crops out in southern Peru. In northern Peru and southern Ecuador the Paleozoic Amotape massif is regarded as an allochthonous terrane accreted by latest Jurassic times (Mourier et al., 1988a). During the Cretaceous it constituted a morphological equivalent of the southern Coastal Cordillera. The coastal Troughs are infilled by very thick sequences of volcanic flows and volcaniclastic deposits of latest Jurassic and Mid-Cretaceous age. They are now exposed along the coast. In northwestern Peru, the Lancones basin constitutes an equivalent of the coastal Troughs which is prolonged into southwestern Ecuador (Celica Trough)(Figure 1). Farther north, coastal Ecuador is made up of allochthonous oceanic terranes accreted during Late Cretaceous to Tertiary times (Feininger and Bristow, 1980) and is not studied in this work.
- The Western Trough received a thick, mainly marine sedimentation during Mesozoic times. It presently crops out in the Western Cordillera. The Western Trough became an incipient Western Cordillera in Senonian times. Its northern end is a lesser subsident area, which constitutes the southward prolongation of part of the Cordillera Real and Subandean zone of Ecuador.
- The Axial Swell is a positive paleogeographic zone characterized by thin deposits during most of the Cretaceous. It now constitutes the Oriental Cordillera of northern Peru (Marañon geanticline), and the southwestern Altiplano of southern Peru (Cuzco-Puno axis).
- The Eastern Basins of Peru and Ecuador were moderately subsiding regions located on the western border of the Brazilian and Guyanese Precambrian shields respectively. They received a mixed marine and continental sedimentation during Mesozoic times. Some positive areas within the Peruvian Eastern Basin were long considered Mesozoic emergent areas (Eastern Cordillera of southern Peru), because they were uplifted and eroded during the Andean orogeny.

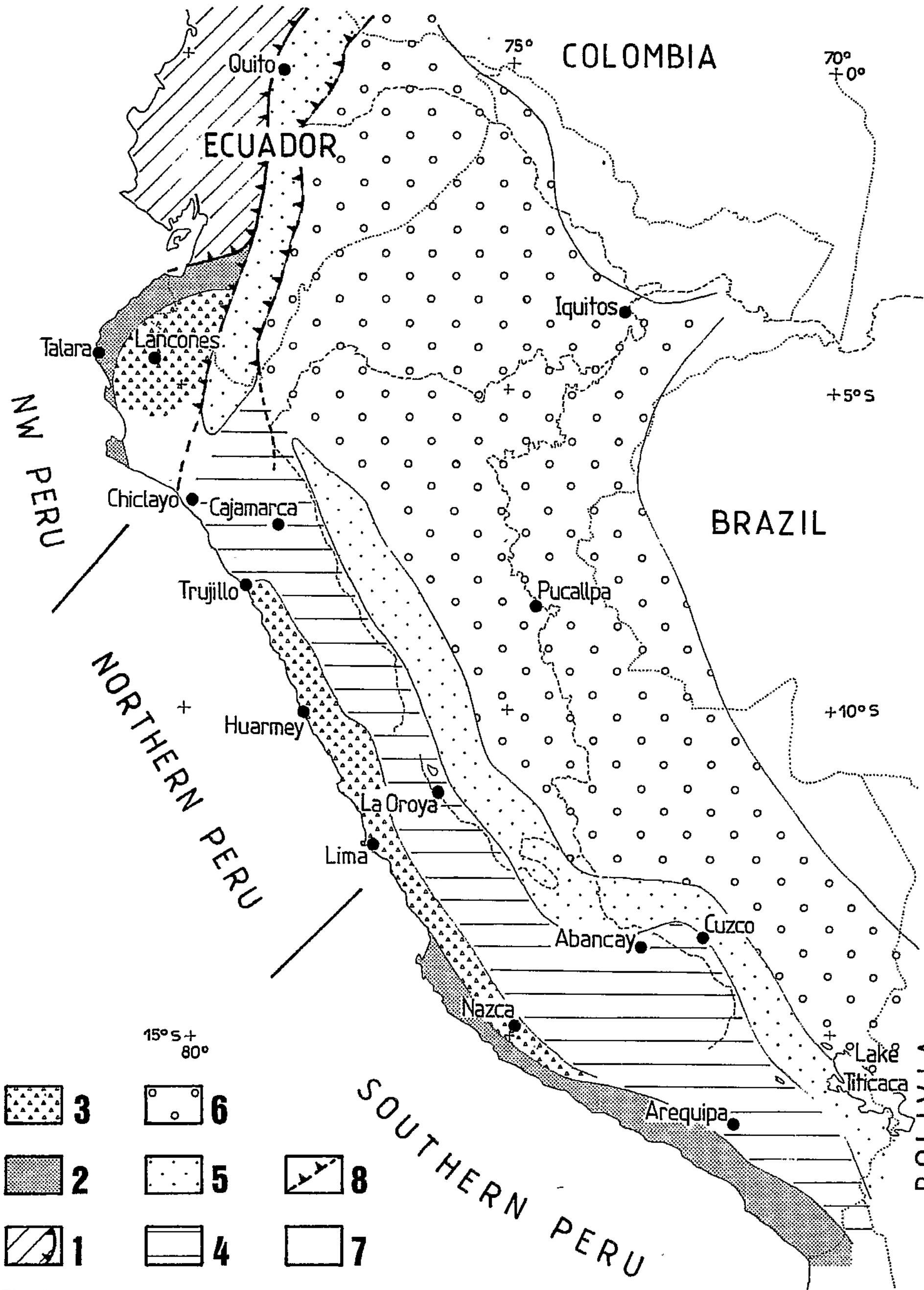


Fig. 1

Paleogeographic sketch of the Peruvian margin, and location of main areas cited. 1: Cretaceous allochthonous terranes, and suture. 2: Coastal Cordillera. 3: Coastal Troughs. 4: Western Trough. 5: Axial Swell. 6: Eastern Basin. 7: Brazilian and Guianese (Colombian) Precambrian shields. 8: Jurassic suture.

In this paper the Peruvian-Ecuadorian margin is divided into three NE trending zones (Figure 1).

Northwestern Peru includes the northernmost part of Peru, west of Chiclayo (Talara-Lancones area), and the southwesternmost part of Ecuador.

Northern Peru is located north of Lima and its eastern part will be described together with Eastern Ecuador. This zone is well-known in the Oriente of Ecuador (Tschopp, 1953; Bristow and Hoffstetter, 1977; Baldock, 1982), and, in Peru, along the Huarmey-Trujillo-Cajamarca-Iquitos line (Benavides, 1956; Soto, 1979; Myers, 1980; Jaillard, 1987; Mourier, 1988), and along a Lima-La Oroya-Pucallpa transect (Rodríguez and Chalco, 1975; Mégard, 1978; Dalmayrac, 1978; Moulin, 1989).

Southern Peru begins south of Lima. It is well-known along the Arequipa-Puno transect (Newell, 1949; Benavides, 1962; Laubacher, 1978; Vicente et al., 1982; Batty and Jaillard, 1989), and in the Cuzco area. The area located west and south of Abancay (Figure 1) is poorly known because of a widespread Tertiary volcanic cover, difficult accesses and recent political troubles.

Cretaceous Stratigraphic Chart and Main Tectonic Periods

Stratigraphic studies make it possible to date the sediments within which sedimentologic and tectonic information is contained. Therefore, revisions of published stratigraphic works, collections of new paleontologic and stratigraphic data and sequence stratigraphy analysis have been carried out and recently synthesized (Jaillard and Sempere, 1989). They make it possible to propose a stratigraphic correlation chart as a working hypothesis (Figure 2). The conversion from stratigraphic stages into absolute ages is made following the timescales of Haq et al. (1987) and Odin and Odin (1990).

Various periods can be recognized during the Cretaceous (Jaillard and Sempere, 1989, Figure 2). However, because the first one begins during latest Jurassic times and the last one ends during Early Tertiary times, we shall consider the Kimmeridgian-Paleocene interval. The Peruvian margin behaved successively: (1) as a mobile unstable region, locally affected by strong volcanic activity (Kimmeridgian-Berriasian); (2) as a stable anorogenic and non-volcanic extensional margin (Valanginian-Aptian); (3) as a stable region whose western part underwent extension-compression alternation, and was the site of outstanding magmatic activity (Late Aptian-Turonian); (4) as a mobile margin undergoing progressive compressional tectonic activity and affected by scarce plutonic intrusions (Coniacian-Campanian); finally, (5) as a relatively stable region which registered some noteworthy magmatic activity (Maastrichtian-Paleocene).

Tectonic Evolution of the Peruvian Margin Between Kimmeridgian and Paleocene Times

Kimmeridgian-Late Berriasian

This is tectonically a very unstable period, which resulted in a contrasting paleogeography (Batty et al., 1990). Several tectonic events can be recognized. However, the paucity of outcrops and the abundance of unfossiliferous continental deposits make accurate analyses and precise paleogeographic reconstructions difficult.

The Kimmeridgian (?) Event

The Kimmeridgian (?) tectonic event is poorly documented, except in southern Peru and in Bolivia (Sempere, this volume).

Northern Peru and Eastern Ecuador

In the Western domains, no Kimmeridgian deposits are known (Benavides, 1956; Rivera et al., 1975; Mégard, 1978; Moulin, 1989; Jaillard and Jacay, 1989). However, they might be represented in northern Peru by the last effusions of the Middle to Late Jurassic volcanic arc, partly dated as Callovian-Oxfordian (Colán Formation, Mourier, 1988) and by the coeval formations of Ecuador intruded by the Zamora and Abitagua plutons (Aspden et al., 1990).
In the Eastern Basins of Peru, undated coarse-grained red beds were deposited during Late Jurassic times (upper Sarayaquillo or Boquerón formations, Rodriguez and Chalco, 1975; Seminario and Guizado, 1976; Pardo and Zuñiga, 1976). They problably correlate with the upper Chapiza Formation of the Ecuadorian Oriente (Tschopp, 1953; Bristow and Hoffstetter, 1977; Baldock, 1982).

Southern Peru

Along the coast, Kimmeridgian deposits could be present in the upper part of the Jurassic detrital deposits of the Guaneros Formation (Vicente, 1981). Farther NE, marine to continental sands and shales may be equivalent to the Labra Formation of the Western Trough (Zuñimarca Formation, Vicente, 1981).
In the Western Trough, widespread silico-clastic shallow marine deposits overlie Callovian-Oxfordian black shales (Labra, Chuquibambilla and Chachacumane formations, Benavides, 1962; Pecho, 1981; Vicente, 1981, 1990; Vicente et al., 1982). In some areas, they disconformably overlie the Callovian shales (Yauca Formation of Olchauski, 1980).
On the Axial Swell and in the Eastern Basin, undated conglomerates (Chupa Formation, Klinck et al., 1986, Huambutío Formation, Carlotto, 1989) rest unconformably upon

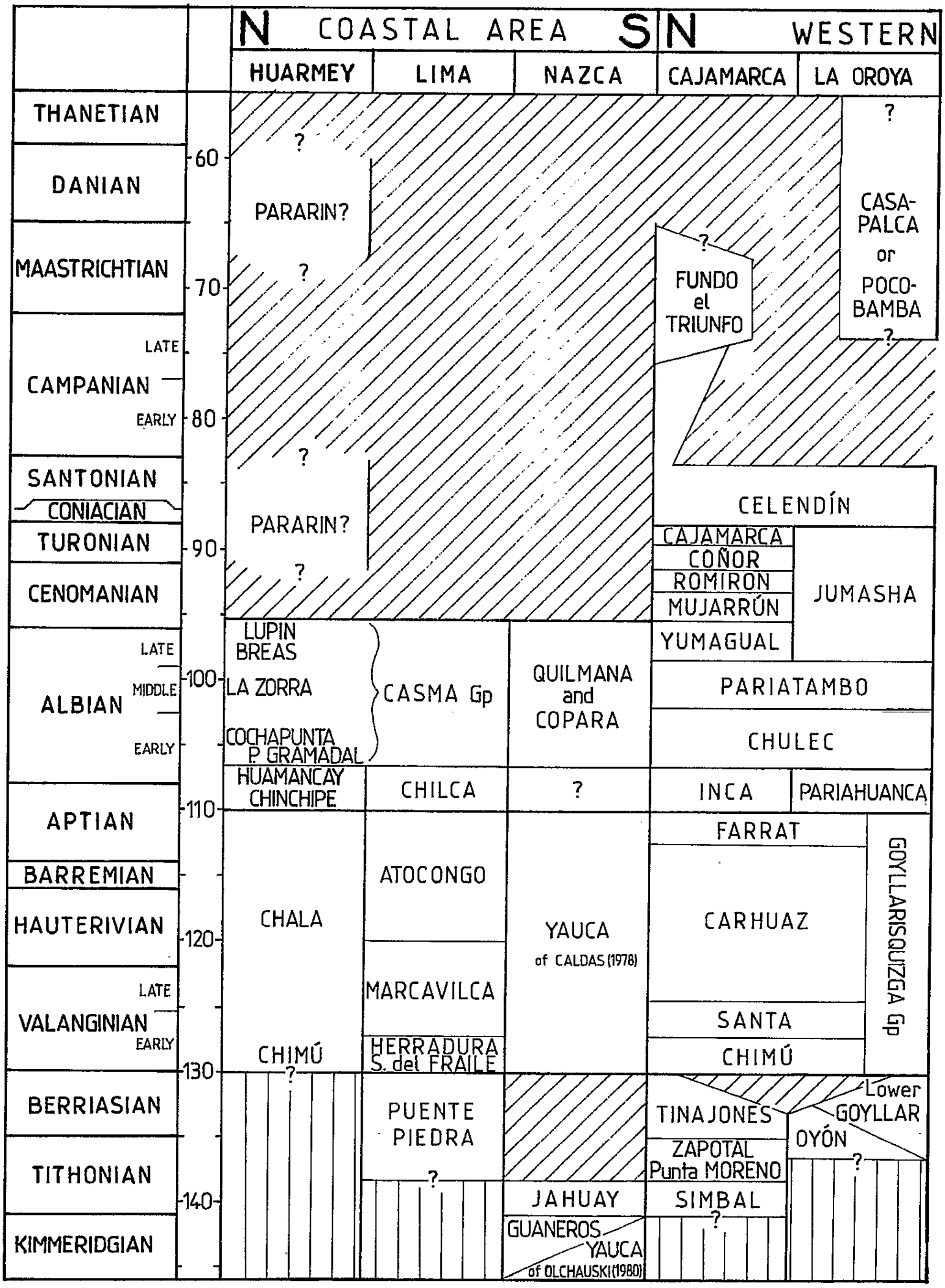


Fig. 2

Correlation chart of the main Kimmeridgian - Paleocene stratigraphic formations of the Peruvian margin. Location on Figure 1.

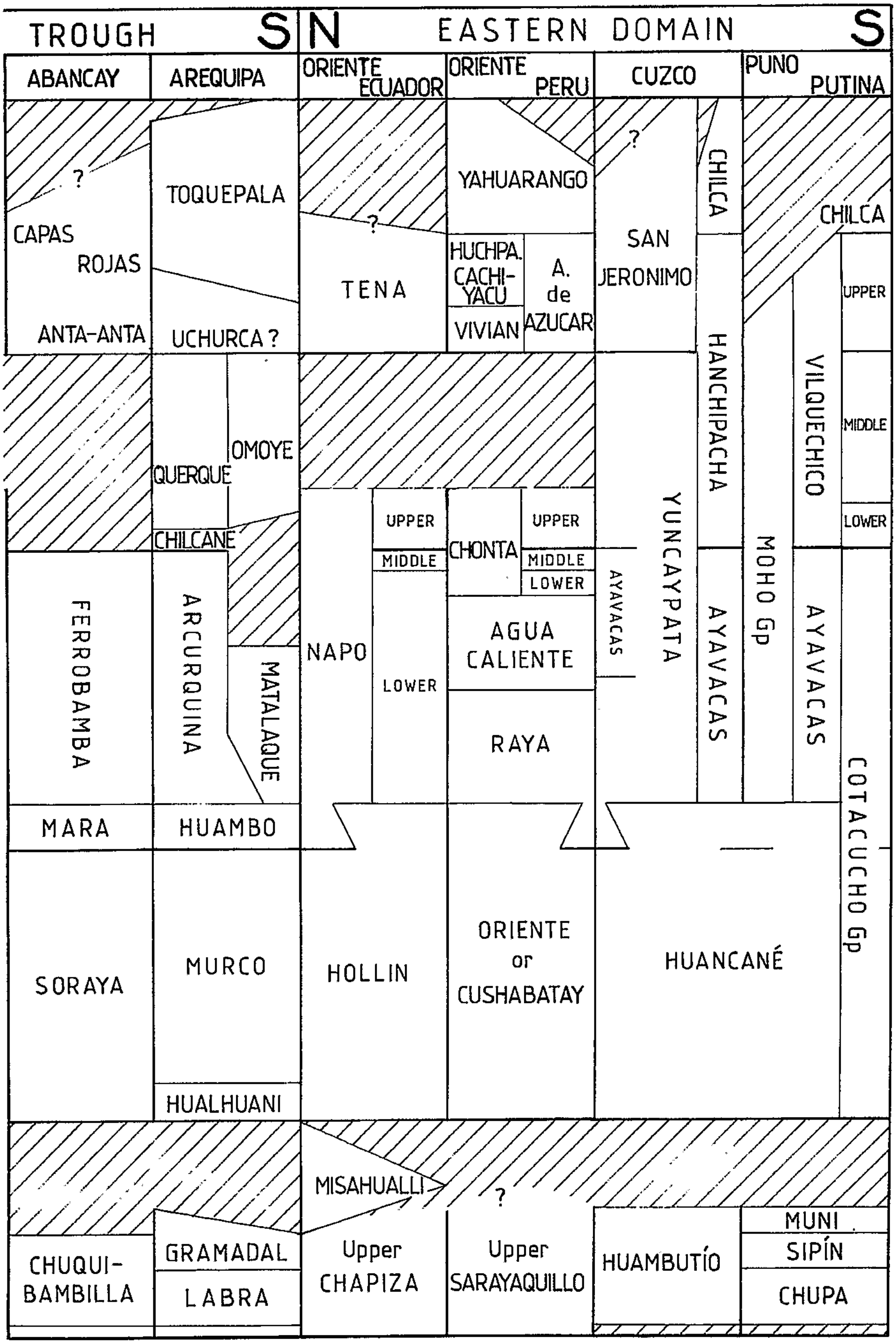


Fig. 2 (Continued)

Paleozoic to Triassic rocks. The dispersion of the paleocurrents and the variations in thickness suggest an uneven paleotopography and an unstable tectonic regime (Figure 3). The Chupa conglomerates roughly correlate with the Condo Formation of Bolivia, which has been interpreted (Sempere et al., 1989) as related to the Kimmeridgian Araucan tectonic event of Argentine and Chile (Stipanicic and Rodrigo, 1969; Riccardi, 1988). Farther northeast, these conglomerates probably correlate with part of the Sarayaquillo Formation.

The Middle Tithonian Phase

In all the western areas of Peru, the Early Tithonian is represented by partly calcareous deposits. These are abruptly overlain by detrital, continental or deep-marine deposits, thus evidencing an important tectonic/paleogeographic event.

Northern Peru and Eastern Ecuador

In the coastal area near Lima, a NW trending trough probably opened during Tithonian times (Figure 6), since marine hemipelagic black shales interbedded among volcanic and volcaniclastic deposits are dated as Late Tithonian-Late Berriasian (Rivera et al., 1975, Wiedmann, 1980). These high-K basalts and andesites are interpreted as the products of a volcanic arc deposited in a back-arc basin (Atherton et al., 1983, 1985).

In the western part of the Western Trough, the partly calcareous lagoonal Simbal Formation is sharply overlain by hemipelagic black shales and then by a 2500 m-thick turbiditic series of Late Tithonian age (Punta Moreno Formation, Jaillard and Jacay, 1989; Jacay, 1991. Numerous olistolites and internal disconformities express a syntectonic depositional setting. The creation of such a subsident trough constitutes a major extensional tectonic event, of Early Late Tithonian age (Jaillard and Jacay, 1989). In the eastern part of the Western Trough, Moulin (1989) describes estuarine red shales and sands of probable Tithonian-Berriasian age (Lower Goyllarisquizga Formation). The geometry of clastic dykes indicates a local NNE-SSW tensional strain (Moulin, 1989, Figure 4). Erosional features beneath the disconformable Valanginian sandstones suggest a hiatus of part of the Late Tithonian-Berriasian deposits (Moulin, 1989).

In the Eastern Basin of northern Peru and Ecuador, the lack of data about the unfossiliferous continental deposits precludes the identification of the Tithonian tectonic event. However, bimodal volcanic flows occurred in the Ecuadorian Oriente and in the northwestern Peruvian Oriente during Tithonian-Berriasian times (Misahualli Formation, Bristow and Hoffstetter, 1977; Hall and Calle, 1982). Farther south, Arthaud et al. (1977) mention NE- and NW-trending Tithonian synsedimentary normal faults.

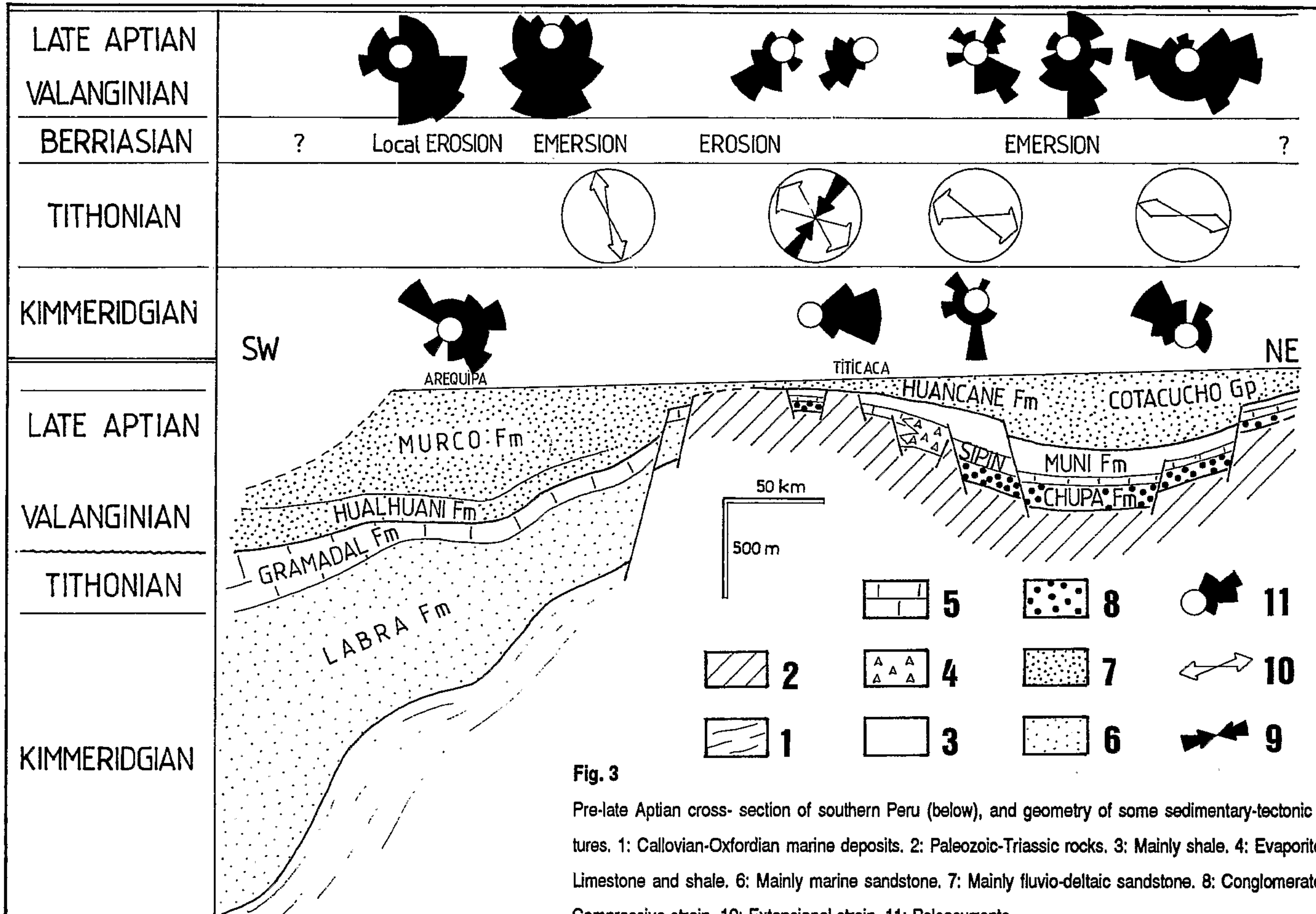


Fig. 3

Pre-late Aptian cross- section of southern Peru (below), and geometry of some sedimentary-tectonic features. 1: Callovian-Oxfordian marine deposits. 2: Paleozoic-Triassic rocks. 3: Mainly shale. 4: Evaporite. 5: Limestone and shale. 6: Mainly marine sandstone. 7: Mainly fluvio-deltaic sandstone. 8: Conglomerate. 9: Compressive strain. 10: Extensional strain. 11: Paleocurrents.

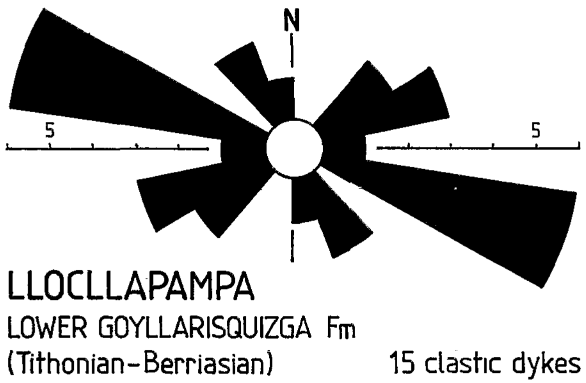


Fig. 4
Orientation of sedimentary clastic dykes in the Tithonian-Berriasian (?) Lower Goyllarisquizga Formation (after, Moulin , 1989).

Southern Peru

In the Western Trough near Nazca, the Early Tithonian partly calcareous Jahuay Formation (Rüegg, 1961) is directly overlain by the Valanginian sandstones (Yauca Formation of Caldas, 1978). There, a stratigraphic gap of Late Tithonian and Berriasian beds is thus probable. In the Arequipa area, Early Tithonian lagoonal sandstones and limestones (Gramadal Formation, Chávez, 1982; Batty and Jaillard, 1989) are overlain by a few tens of meters of red shales (Batty, in preparation, Figure 6). In other areas, the Valanginian sandstones seem to directly and conformably overlie the Kimmeridgian (?) sandstones (e.g. Olchauski, 1980; Pecho, 1981, 1983).

On the axial Swell and in the eastern region (Altiplano), Late Jurassic limestones and shales (Sipín Formation, Newell, 1949) probably correlate with the Gramadal Formation (Laubacher, 1978; Batty and Jaillard, 1989). They give way upward to tidal and continental red shales and thin-bedded sandstones (Muni Formation, Newell, 1949), which are in turn disconformably overlain by the Valanginian sandstones (Huancané Formation). In the Cuzco area, the undated Huambutío Formation exhibits a comparable sequence (Carlotto, 1989). On the Altiplano and in the northeastern part of the Western Trough, the Early Tithonian is marked by synsedimentary tectonic structures, such as normal faults, slumpings and clastic dykes (Figures 3 and 5). A geometrical study of these features indicates a NW- to WNW-trending tensional stress during Tithonian times (Jaillard and Batty, 1989), whereas scarce reverse synsedimentary faults suggest a normal NE-SW compressional component (Figure 5).

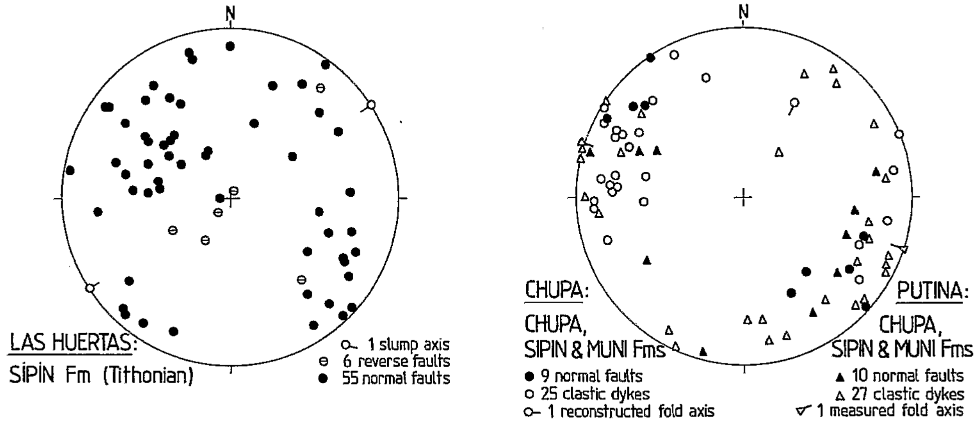


Fig. 5

Poles of synsedimentary faults and clastic dykes in the early Tithonian Sipín Formation of the Altiplano (eastern area, southern Peru).

The Berriasian Event

This is mainly expressed by a regional disconformity beneath the Valanginian sands (see Tschopp, 1953; Benavides, 1956; Pardo and Zúñiga, 1976; Laurent, 1985; Jaillard and Sempere, 1989; Figures 5 and 6).

Northern Peru and Eastern Ecuador

Along the coast, marine sedimentation and volcanic arc effusions went on until latest Berriasian times in the Lima area (Puente Piedra Formation, Wiedmann, 1980; Atherton et al., 1985, Figure 6).

In the Western Trough, near Trujillo, Late Tithonian turbidites are overlain by latest Tithonian black shales, and then by Berriasian (?) shallow marine to deltaic sandstones (lower part of Tinajones Formation, Cobbing et al., 1981; Jaillard and Jacay, 1989). This formation exhibits numerous synsedimentary normal faults, thus expressing an extensional instability (Jaillard and Jacay, 1989). It probably correlates southward with the deltaic Oyón Formation of the Lima area (Mégard, 1978; Cobbing et al., 1981). The overlying fluvial red beds (upper part of Tinajones Formation, Jaillard and Jacay, 1989) are only very locally preserved beneath the Valanginian sandstones, thus illustrating the pre-Valanginian erosional unconformity (Figure 6).

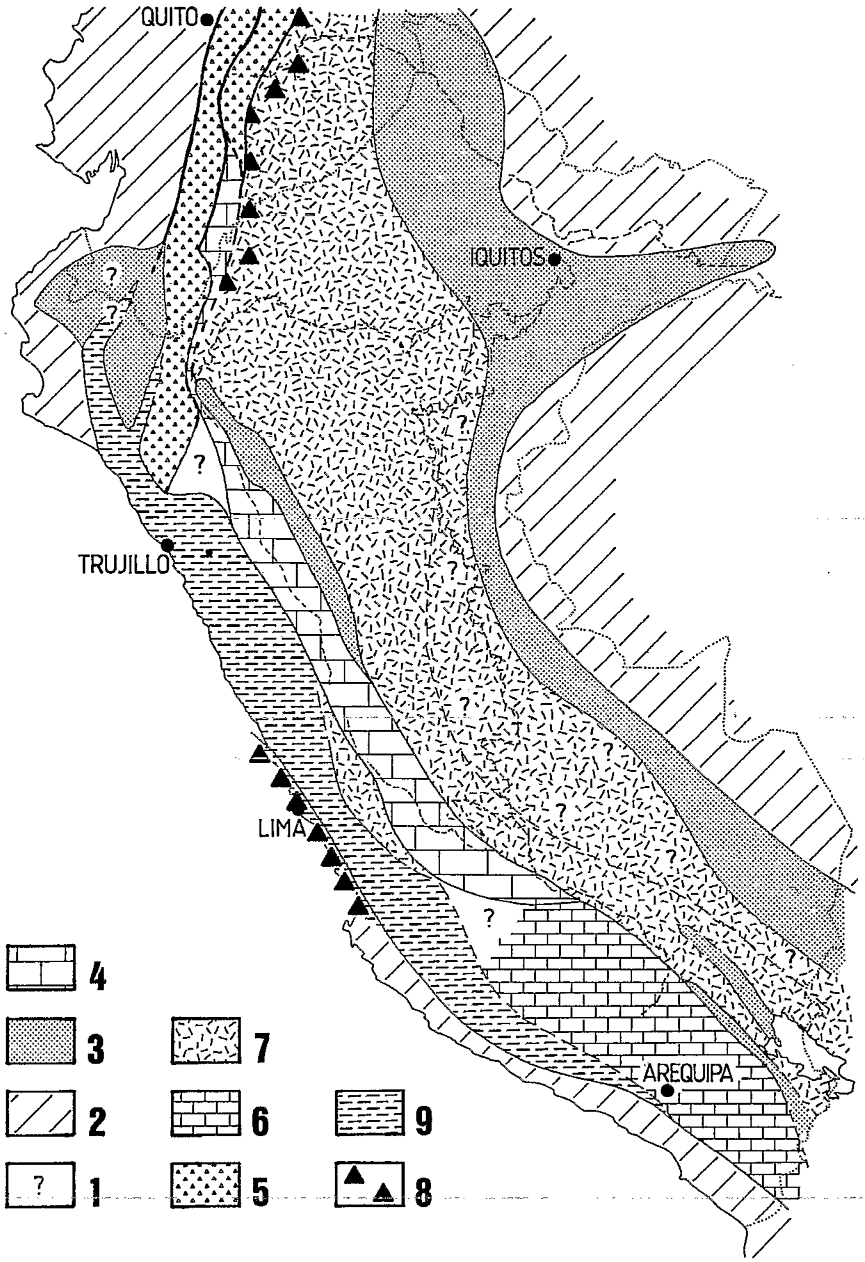


Fig. 6

Pre-Valanginian geological sketch map. 1: No pre-Valanginian outcrops. 2: No Valanginian deposits. 3: Pre-Norian rocks. 4: Norian to Middle Jurassic limestone. 5: Middle to Late Jurassic volcanic and volcaniclastic rocks (volcanic arc). 6: Early Tithonian limestone and shale. 7: Late Jurassic continental Red Beds. 8: Late Tithonian - Berriasian volcanic rocks. 9: Berriasian deltaic to marine deposits.

In the Oriente of Peru and Ecuador, the bimodal effusion of the Misahualli Formation could have continued during Berriasian times (Bristow and Hoffstetter, 1977).

Southern Peru

In the western part of the Western Trough, Late Tithonian-Berriasian marine to deltaic black shales and fine-grained sandstones probably correlate with the Oyón Formation (Bellido, 1956; Tiabaya outcrops, Geyer, 1983).

In the Western Trough and near the Axial Swell, no tectonic event has been clearly recognized, since the Valanginian sandstones disconformably overlie the often eroded post-Early Tithonian red beds, and Late Tithonian-Berriasian deposits are most probably lacking (see above, Figures 3 and 6). It suggests that these areas were emergent during Berriasian time (Batty and Jaillard, 1989; Batty et al., 1990, Figure 6).

Tectonic Interpretations

The Kimmeridgian tectonic event (ca 145-142 Ma): A distal response to the Argentina-Chilean Araucan phase?.

No information is available in northern Peru about the Kimmeridgian event. It is mostly expressed in southern Peru by the resumption of detrital sedimentation and by the instability of the uneven substratum (Figure 3). It seems to represent a distal response to the Argentina-Chilean Araucan tectonic phase of Kimmeridgian age (see Sempere, this volume).

The Middle Tithonian tectonic event (ca 138-137 Ma): Oblique collision and coastal extension.

The shape of the turbiditic trough of northwestern Peru, the high sedimentation rate and the strong initial tectonic subsidence strongly suggest this trough to be an extensional, probably pull-apart basin (Jaillard and Jacay, 1989), related to the oblique dextral collision of the Amotape allochthonous continental terrane (Mourier et al., 1988a; Mourier, 1988). In the Cordillera Real of Ecuador, a major collisional tectonic phase caused the folding, thrusting and metamorphism of Jurassic arc-related volcanic rocks, and is also regarded as related to the accretion of continental blocks (Aspden et al., 1988; Litherland and Aspden, 1990). It is probable that the latter phase correlates with the Tithonian tectonic event of northern Peru. Although no structural data is available about the pre-Cretaceous deformations of the Peruvian Jurassic volcanic arc, the contrasting paleogeography sealed by the Valanginian sandstones (Figure 6), the significant variations in thickness of the latter (Figure 7), and the abundance of volcanic clasts in the eastern upper Sarayaquillo Formation suggests that an important pre-Cretaceous tectonic event affected the Jurassic volcanic rocks.

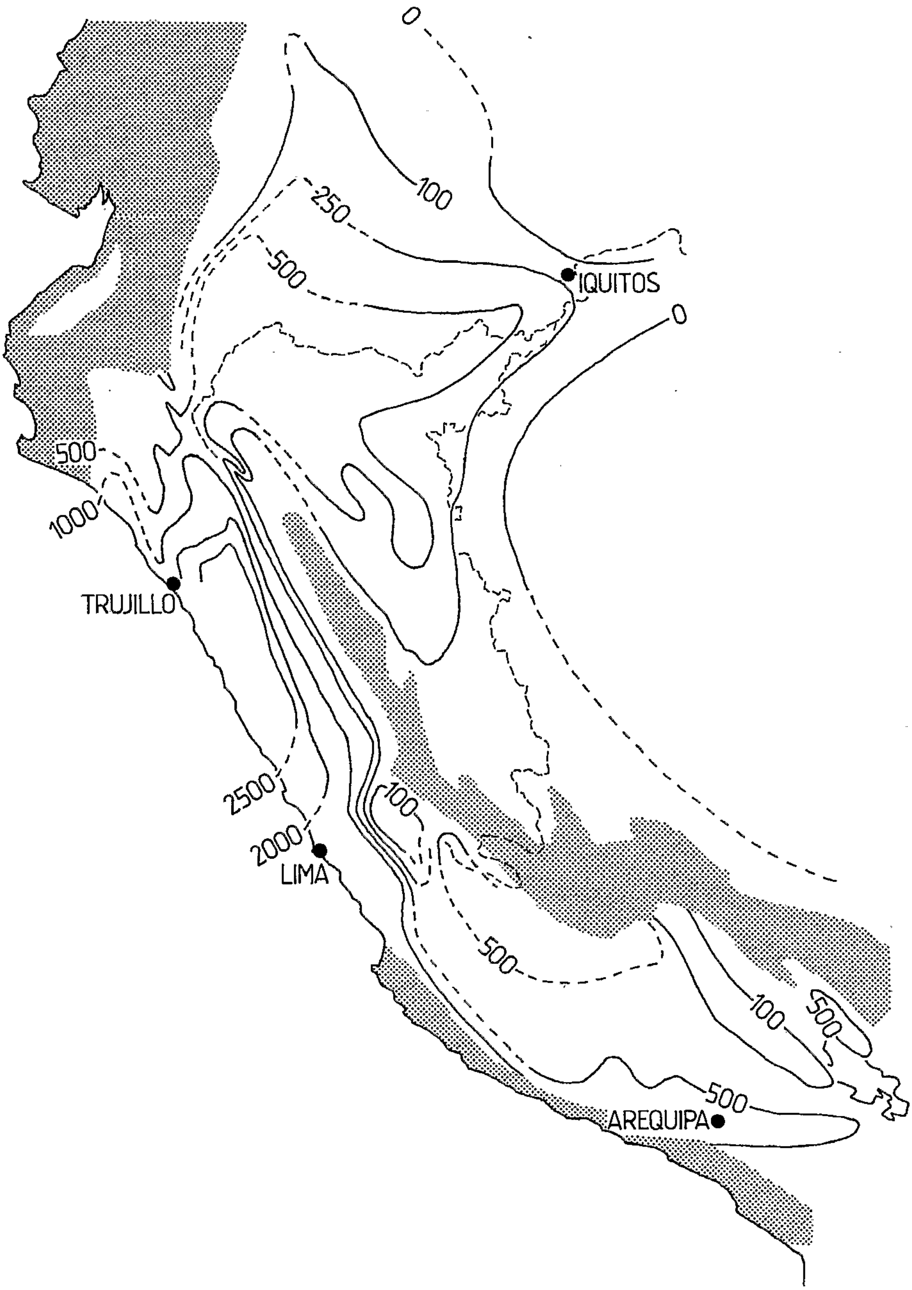


Fig. 7

Isopach map of Valanginian- late Aptian deposits. Shaded areas: no early Cretaceous deposits.

Nevertheless, farther south, extension seems to have been dominant. The opening of a Tithonian back-arc basin in the Lima area expresses an extensional tectonic regime, which could be associated with important strike-slip movements (Atherton et al., 1985). In eastern and southern Peru, a roughly NNW-SSE tensional strain, possibly associated with a NE-SW compression, and a subsequent regional emergence are recorded.

The Tithonian tectonic event can therefore be interpreted as the result of an oblique dextral collision of allochthonous terranes, generating oblique compression in northwestern Peru and Ecuador, whereas a roughly NNW-SSE extensional stress seems to have been dominant in the rest of Peru. However, the relationships between the northern compressional-wrenching regime and the southern extensional one are not well understood, and the NE-SW compression may have been more important than presently assumed.

The Berriasian tectonic event (ca 134-129 Ma): Further extensional phase and incipient northern South Atlantic rifting.

In northernmost Peru, the Berriasian event is characterized by an extensional tectonic instability and by bimodal volcanic effusions regarded as a Late stage of the continental accretion, probably represented by dextral wrenching movements (Jaillard and Jacay, 1989). In the rest of the Peruvian margin, the Berriasian event is marked by a stratigraphic gap and/or by erosions (Figures 3 and 6), and probably corresponds to a regional uplift. However, the Tithonian and Berriasian events are frequently confused and cannot be distinguished through the sedimentary record, because of the Late Tithonian gap.

The subsequent deposition of widespread, east-deriving sandstones suggests that an uplift of the eastern areas and a sinking of the western ones occurred during latest Berriasian times. Thus, the Berriasian event can be interpreted, according to the regions, either as a new manifestation of the extensional stress which dominated since Tithonian time, or as a genetically independant tectonic event related to the incipient rifting of the South-Atlantic ocean and resulting in the westward tilting of the entire South-American plate.

Valanginian-Early Late Aptian

This period is characterized by widespread silico-clastic deposits (Goyllarisquizga Group, Hollín Formation) and by a tectonic and magmatic quiescence. The fluvio-deltaic sedimentation is mainly controlled by eustatic sea-level fluctuations (Moulin, 1989; Moulin and Séguret, in press). In the coastal zone, marine partly calcareous deposits prevailed locally after Valanginian times (Rivera et al., 1975).

The isopach map for Early Cretaceous times (Figure 7) suggests that the shape of the sedimentary basins is controlled by and is the consequence of the Tithonian and Ber-

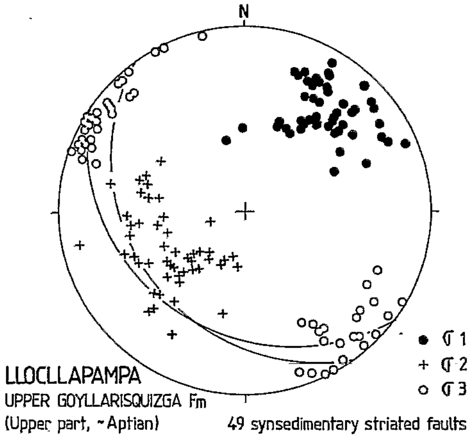


Fig. 8

Local Aptian extensional stress (top of Goyllarisquizga Formation) (after, Moulin, 1989).

riasian tectonic events. It reveals the three classical components of Cretaceous paleogeography (Benavides, 1956): a very subsident western region (West-Peruvian Trough), and an eastern less subsident one (East-Peruvian Trough, Ecuadorian Oriente), both regions being separated by a paleogeographic high with reduced sedimentation (Marañon Geanticline). Moreover, one can recognize a northern subsiding region and a southern much less subsident one, separated by a positive block located NE of Lima.

In northern Peru, the strong differential subsidence (Figure 7) suggests that synsedimentary normal faults parallel to the trench were active, and a tensional strain regime can be inferred. Paleocurrents indicate that the detrital material was supplied by the eastern shields, and that it was transported perpendicularly to the isopach curves, indicating a general trenchward gently-dipping paleoslope. In southern Peru, the extensional stress seems to have been much weaker.

The only reported synsedimentary tectonic features occurred in the Western Trough of central Peru. There, in the Goyllarisquizga Formation, Moulin (1989) mentions synsedimentary normal faults, indicating a progressive rotation of the local tensional stress from WNW-ESE in the lower part to NNW-SSE in the Middle part and to NE-SW in the upper part (Figure 8).

Except for the single 122 Ma K-Ar whole-rock age of Southeastern Peru (Crucero area, Clark et al., 1990), no volcanic manifestations have been reported so far within the deposits of the Western Trough. Along the coast, some Neocomian K-Ar ages within volcanic-sedimentary formations (124-128 Ma, Vidal et al., 1990) suggest that magmatic activity occurred locally. However, they could also represent minimum ages of older Tithonian-Berriasian rocks.

The eastern origin of the clastic supply suggests that it was generated by a large-scale westward tilting of the South American plate, which can be interpreted as the result of both the incipient rifting of the northern South Atlantic ocean (doming?), and the extensional subsidence of the western areas. However, the sudden development, and very large extension of the fluviodeltaic sedimentation suggests that the climate also changed drastically, becoming much more humid.

Late Aptian-Late Turonian

This time-span is characterized by a widespread marine transgression which permitted the deposition of successive carbonate shelves in the Western Trough, grading laterally to deltaic deposits in the Eastern Basin. Two tectonic periods can be recognized. The first (Late Aptian-Early Middle Cenomanian), corresponds to the evolution and accretion of a volcanic arc, or an extensional marginal basin ("Mochica" events, Mégard, 1984). The second (Middle Cenomanian-Late Turonian), is characterized by high depositional rates and by tectonic and magmatic quiescence.

The Late Aptian-Earliest Albian Event

Late Aptian-earliest Albian times are characterized by a widespread marine transgression (Jaillard, 1987; Moulin, 1989; Batty and Jaillard, 1989), by scattered volcanic manifestations and by local extensional tectonic events.

Northwestern Peru

In the Lancones Trough, possible Late Aptian-earliest Albian volcanic events could be represented by tuffaceous layers interbedded in the thick, poorly-dated sedimentary San Pedro Group (Reyes and Caldas, 1987).

Northern Peru and Eastern Ecuador

In the coastal area, thick conglomerates (Chinchipe Formation) are overlain by a Late Aptian-earliest Albian shaly sequence (Myers, 1974, 1980). In the Lima area, the presence of *Parahoplites* in the 2500 m-thick volcanic Chilca Formation (Rivera et al., 1975) shows that volcanic activity began locally as early as the Late Aptian-earliest Albian.

In the Cajamarca area of the Western Trough, the base of the Inca Formation locally exhibits erosional features, disconformities, or thin conglomerates or breccias (Jaillard, 1987). Scarce small-scale synsedimentary faults and slumps are also present, as well as local sulphide-bearing acidic volcanic flows and tuffs (Paredes, 1982, Figure 9). Farther south, the Pariahuanca Formation contains scarce basaltic flows, which exhibit an alkaline chemical trend, indicating an intracontinental extension (Soler, 1989, Figure 9).

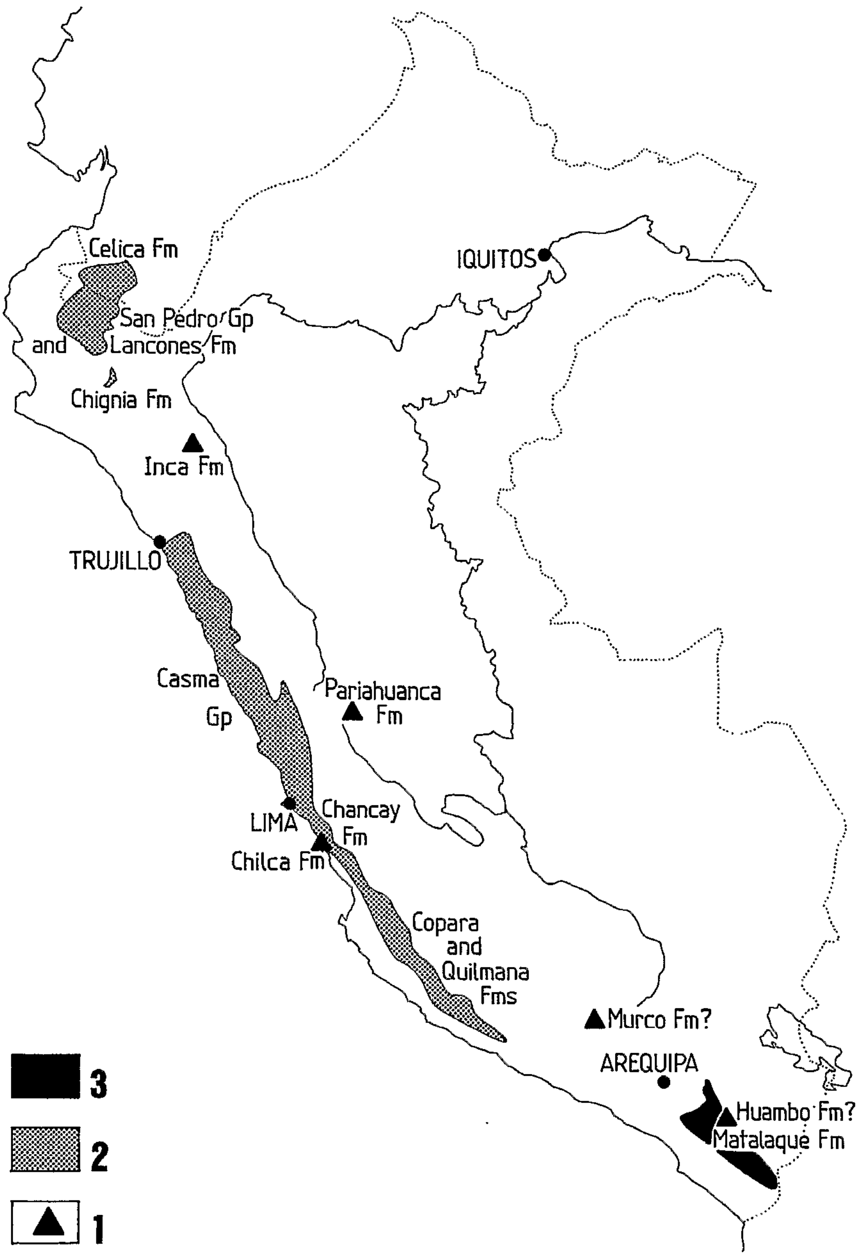


Fig. 9

Sketch map of the main late Aptian - Cenomanian volcanic events in Peru. 1: Local late Aptian-earliest Albian volcanic flows. 2: Marine, thick volcanic sequences of early Albian-Cenomanian age. 3: Continental, thick volcanic sequences of Albian-Cenomanian age.

the base of the same formation, Moulin (1989) mentions clastic dykes expressing a NE-SW extension.

In the Oriente of Peru and Ecuador, the marine transgression is only observed in the western areas. Farther east, sandstone deposition seems to have continued.

Southern Peru

Along the coast, near Ilo, plutons began to be emplaced (111 Ma, Beckinsale et al., 1985). In the Western Trough, dacite, rhyolite and andesite flows are interbedded in the Huambo Formation (Pérez, 1981; Loza, 1988; Batty, in preparation, Figure 9). However, the correlation of this undated formation with the Inca Formation is not verified throughout, and the associated volcanic flows might represent either earlier (Mid-Aptian?) or younger events (base of the Matalaque Formation, Mid-Albian?).

The Early and Middle Albian Events

During this time-span, the marine transgression reached its maximum extent, and a discontinuous belt of coastal volcanic centres was active (Figure 9).

Northwestern Peru and Southwestern Ecuador

The Lancones basin received a thick volcanic and volcaniclastic sequence of basaltic, andesitic, dacitic and rhyolitic rocks of Albian age (Ereo and La Bocana formations, Reyes and Caldas, 1987, San Lorenzo Group, Beaufils, 1977 in Mourier, 1988, Figures 9 and 13). It correlates with the Celica Formation of Ecuador (Feininger and Bristow, 1980; Baldock, 1982). The Celica Formation has been interpreted by most of the authors as a volcanic arc (Baldock, 1982; Lebrat et al., 1987; Wallrabe-Adams, 1990) but more recently Aguirre (1990) suggested that it could represent an aborted ensialic marginal basin. The Celica Formation is intruded by a pluton which yielded a 113 Ma K-Ar age (Baldock, 1982), thus suggesting that volcanic activity started before Aptian times.

Northern Peru

Along the coast, thick volcanic flows and volcaniclastic deposits are interbedded with marine shales, limestones and cherts of Early and Middle Albian age (Casma Group, Myers, 1974, 1980; Guevara, 1980) (Figure 9). Numerous coarse-grained turbidites and slumpings indicate the vicinity of an active volcanic arc and/or an unstable tectonic regime (Atherton and Webb, 1989). The thick basalt and andesite flows, pillow-lavas, tuffs and hyaloclastic rocks, with subordinate dacites and rhyolites of the Casma Group, exhibit a tholeiitic trend (Soler, 1991b). They were laid down in an extensional tectonic regime, which has been attributed (1) to a back-arc ensialic marginal basin setting (Atherton et al., 1983, 1985; Aguirre et al., 1989), (2) to a true ocean-floored marginal basin (Atherton, 1990), or (3) to the extensional tectonic subsidence of a volcanic arc (Soler, 1991a, 1991b)(see discussion in Mochica Period, p. 156-157). The great apparent thickness of the volcanic series (2000 to 8000 m, Figure 13) and the high geothermal gradient led Aguirre and Offler (1985) to admit to a considerable stretching of the underlying continental crust.

However, Mid-Albian plutons (102 Ma, Wilson, 1975) cross-cut folded Albian volcanic rocks of the Casma Group (Myers, 1975; Cobbing et al., 1981; Bussel and Pitcher, 1985), thus indicating that compression also occurred during the Early Albian. Moreover, pre -and syn-tectonic foliated early basic intrusions were emplaced (Patap super-unit, Beckinsale et al., 1985; Soler and Bonhomme, 1990).

In the Western Trough, numerous basalt and andesite sills and dykes in the Mid-Albian deposits (Pariatambo Formation) exhibit an alkaline chemistry, and indicate that an intracontinental extensional stress also affected the surrounding areas (Soler, 1989).

Southern Peru

Along the coast, between Lima and Nazca, thick accumulations of basalts and basaltic andesites (1000 to 2000 m, Copara and Quilmana formations, Figure 9) are interbedded with marine partly bituminous sediments, and unconformably overlie the Neocomian-Aptian sandstones (Caldas, 1978). Though an earlier age has been proposed (Caldas, 1978), they contain fauna of Albian affinity. The volcanic material has a clear calc-alkaline affinity, and is interpreted as having issued from a volcanic arc (Injoque, 1985; Soler, 1989). South of Arequipa, tonalite intrusions continued near Ilo (111 to 99 Ma, Beckinsale et al., 1985; Clark et al., 1990), thus indicating some early magmatic activity of Late Aptian to Mid-Albian age.

In the southwestern part of the Western Trough, up to 2500 m of terrestrial andesites, dacites and overlying agglomerates (Matalaque Formation, Marocco and Del Pino, 1966; Vicente, 1981, Figures 9 and 13) unconformably overlie either the Neocomian-Aptian Murco Formation or the Late Aptian-Early Albian (?) Huambo Formation, through an erosional surface (Batty and Jaillard, 1989). Geochemical study of the trace elements indicates a subduction-related volcanic arc origin for the Matalaque Formation (Carlier and Soler, personal communication, 1990). Although its age is poorly coordinated, this well-defined volcanic crisis seems to correlate roughly with the Albian to Mid-Cenomanian volcanic event.

Neither volcanic sills nor dykes have been observed in the western and eastern regions of southern Peru.

The Late Albian-Early Middle Cenomanian Phase

This period is characterized by a major marine regression that permitted deltaic deposits to extend southwestward (Figure 10). It is contemporaneous with the compressional deformation of the coastal volcanic centres, with precursory intrusions of the coastal Batholith, and with important synsedimentary deformations.

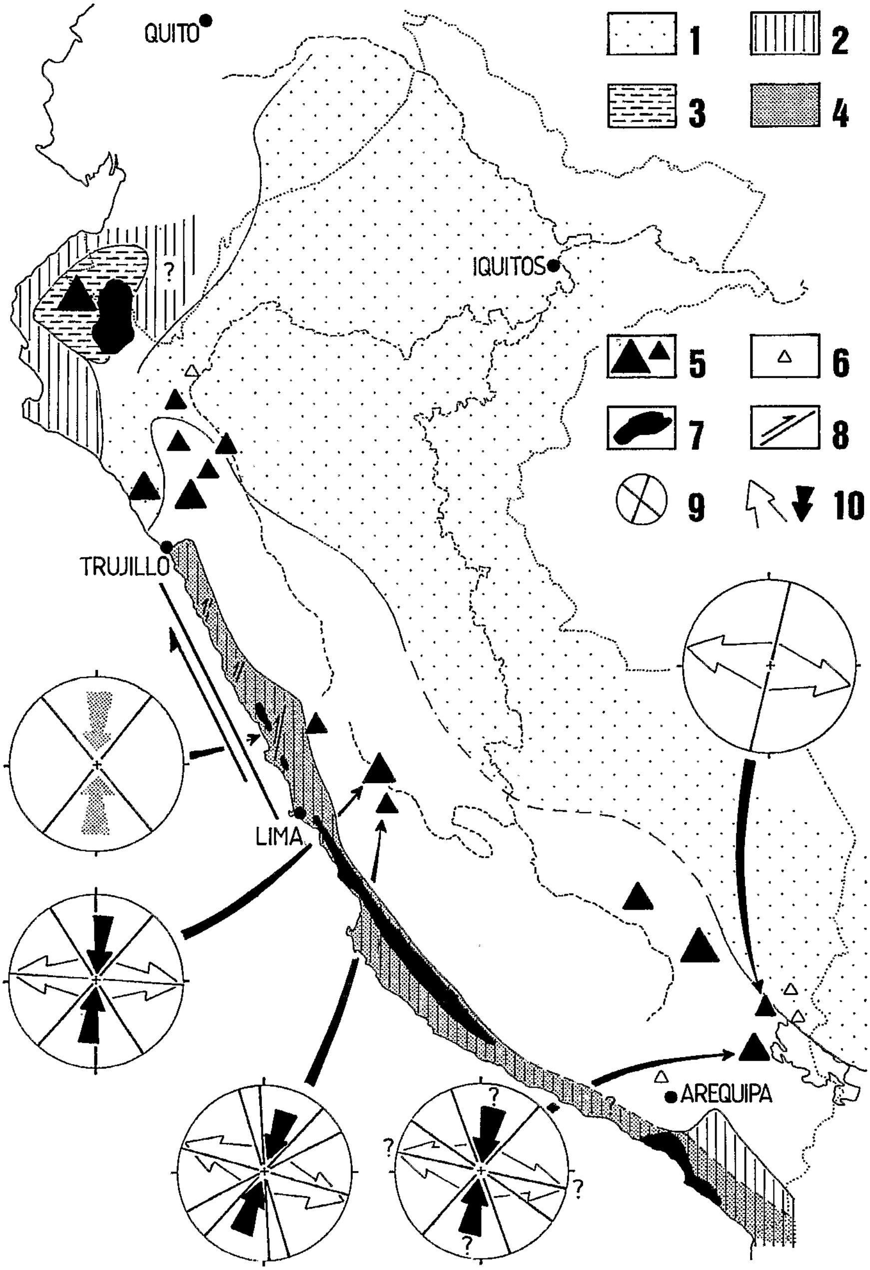
Northwestern Peru and Southwestern Ecuador

In the eastern part of the Lancones Trough, the thick Albian volcanic effusions are unconformably overlain (basal conglomerate) by Late Albian-Cenomanian breccias, pyroclastites and intermediate to acidic flows (Lancones Formation, Reyes and Caldas, 1987; Beaufils, 1977 in Mourier, 1988). These rocks merge laterally westward into Cenomanian to Senonian turbidites, interbedded with volcanic flows (Copa Sombrero Formation of Peru, Morris and Aleman, 1975; Reyes and Caldas, 1987, Alamor Group of Ecuador, Bristow and Hoffstetter, 1977; Baldock, 1982). Farther west, the turbidites overlie the Albian-Cenomanian limestones of the western border of the Lancones Trough (Morris and Aleman, 1975; Mourier, 1988).

Northern Peru and Eastern Ecuador

Along the coast, compressive deformation occurred during Late Albian and Cenomanian times, alternating with tensional periods (Bussel, 1983; Bussel and Pitcher, 1985). Intrusions of syntectonic gabbros and diorites continued (Patap unit, Cobbing et al., 1981; Pitcher et al., 1985), and they precede the emplacement of the coastal Batholith itself (Pitcher et al., 1985; Soler and Bonhomme, 1990). The subaerial nature of the overlying volcanic Pararin Formation (Myers, 1974) indicates that the Casma volcanic complex emerged. In the Lima area, marine conditions continued until Early Cenomanian times, as witnessed by the presence of *Mortoniceras* sp. and *Mantelliceras* sp. in the upper part of the Casma Group (Guevara, 1980). This compressional deformation was probably associated with important dextral wrenching motions (Myers, 1974; Bussel and Pitcher, 1985, Figure 10). The deformations observed in the western part of the Casma Group consist of mainly NW-trending and subordinate NE-trending open folds, commonly associated with a steep dipping axial plane cleavage (Myers, 1974; Mégard, 1987). In the eastern part, stronger deformations and cleavages are observed along the contact with the Western Trough.

In the northern part of the Western Trough, some slumpings, synsedimentary normal faults, large clastic dykes, and breccias in Late Albian and Early Cenomanian limestones are interpreted as the response to the compressive phase in this area (Jaillard, 1987, Figure 10). These features, as well as the pronounced differential subsidence in some


QUITO
IQUITOS
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LIMA
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areas (Jaillard, 1987), suggest a rather extensional paleo-stress. Northeast of Lima, beds of breccias (locally tens of metres thick) and synsedimentary normal faults and slumpings in the dolomitic lower part of the Jumasha Formation indicate a notable tectonic activity during the Early Cenomanian regression, and are regarded as a consequence of the Late Albian-Early Middle Cenomanian phase (Jaillard, 1987, Figure 10). The geometric analysis of these synsedimentary structures reveals the existence of two fracture systems, which trend NE-SW to ENE-WSW and NNW-SSE to N-S, respectively (Figure 11). A minor, NNE-SSW trending fracture group is associated with scarce reverse synsedimentary faults. Slump fold axes are mainly E-W trending and indicate a southward-dipping paleoslope (Figure 11). These features express a WNW-ESE tensional stress associated with a minor NNE-SSW compression (Figure 10).

In the Eastern Basin of Peru and Ecuador, the effects of the Late Albian-Early Middle Cenomanian phase are poorly known, because of unsatisfactory outcrop conditions. However, the westward progradation of the Late Albian-Cenomanian delta (Agua Caliente Formation of Peru, Rodriguez and Chalco, 1975; Soto, 1979; Middle sandstones of the lower Napo Formation of Ecuador, Tschopp, 1953), which seems mainly due to the Early Cenomanian eustatic regression, may have been accentuated by a mild uplift correlative with the tectonic event (Jaillard, 1987).

Southern Peru

Along the coast, no structural data are available on the Albian-Cenomanian volcanic series (Copara and Quilmana formations) which are directly capped by Tertiary deposits (Caldas, 1978; Anónimo, 1980). The plutonic activity seems to have been very low (Soler and Bonhomme, 1990), except in the Nazca area, where well-dated plutons were emplaced during Middle Albian-Middle Cenomanian times (101 to 94 Ma, Beckinsale et al., 1985; Mukasa, 1986).

In the western part of the Western Trough, the volcanic activity probably ceased, since the Senonian (?) Omoye Formation (García, 1978) disconformably overlies the already weathered Matalaque Formation, thus suggesting that a large interval of subaerial expo-

Fig. 10

Sketch map of the late Albian-early middle Cenomanian deformations in Peru. 1: Maximum extent of the deltaic influence. 2: Emergent areas. 3: Turbiditic troughs. 4: Folded areas. 5: Synsedimentary tectonic features (size of triangles is roughly proportional to the importance of the deformation). 6: No observed deformation. 7: Late Albian-Cenomanian intrusions of the Coastal Batholith. 8: Dextral wrench faults (after Bussel, 1983; Bussel and Pitcher, 1985). 9: Late Albian-early middle Cenomanian joint fractures (data north of Lima from Bussel and Pitcher, 1985). 10: Late Albian- early middle Cenomanian interpreted stress (north of Lima: personal interpretation).

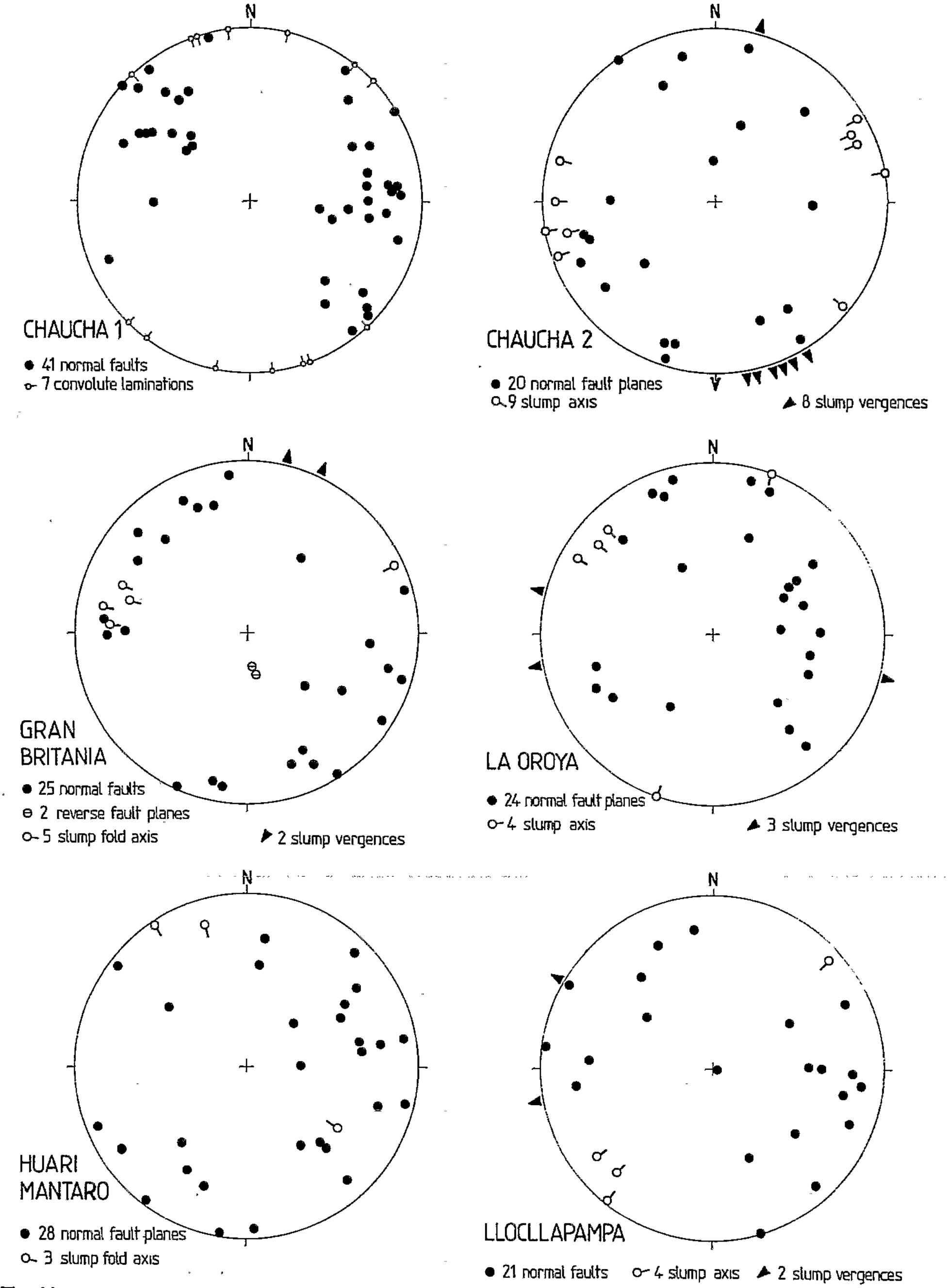

Fig. 11

Geometry of late Albian- early middle Cenomanian synsedimentary tectonic structures in the central Peruvian margin (Jumasha Formation).

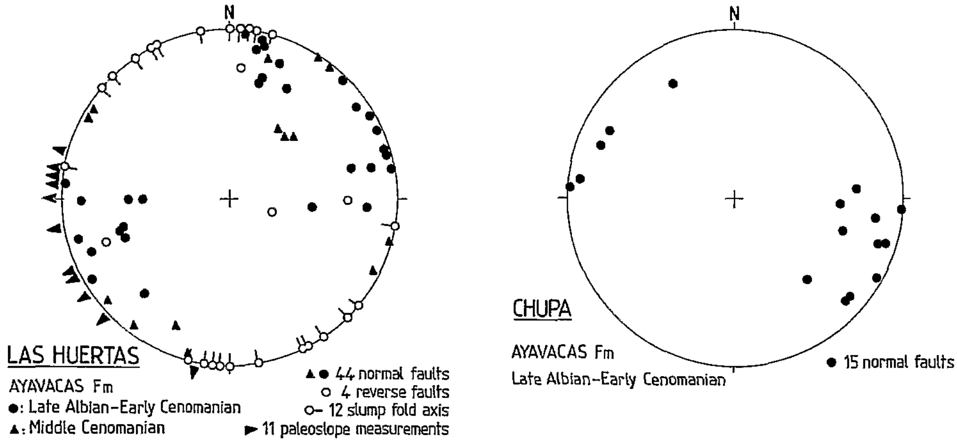

Fig. 12

Geometry of late Albian- early middle Cenomanian synsedimentary tectonic structures in the south Peruvian margin (Ayavacas Formation).

sure and alteration occurred before the Senonian (Figure 10). Moreover, the intercalations of volcanogenic sandstones, within the probably Early to Middle Cenomanian regressive horizons of the Arcurquina Formation, suggest that the Matalaque Formation was at least partly eroded at this time. However, no detailed studies have been made so far of the pre-Senonian deformation of the Matalaque Formation. In the eastern part of the Western Trough, no important synsedimentary deformations have been reported in the Arcurquina Formation, but neither are there any detailed studies available.

Near the Axial Swell and in the Eastern Basin, some noteworthy synsedimentary deformations are known in the Ayavacas limestones (Figure 10). In the Sicuani area, Audebaud (1971, 1973) describes large-scale mass slumping and collapses, angular unconformities and karstifications. In the Puno and Cuzco areas, synsedimentary breccias, slumpings, faults and gravity slides are also present (Portugal, 1974). In many cases the Mid-Cretaceous age of the deformation is attested to by the discordancy of overlying strata (upper Ayavacas, Hanchipacha and Vilquechico formations, Audebaud, 1971; Jaillard, unpublished). Geometrical analysis of the deformational structures evidences a dominant NNW-SSE direction of the normal faults and a WSW-ward associated paleoslope (Figure 12), which is supported by the westward slides observed by Audebaud (1971) and by the eastward thinning and increasing erosions of the coeval Miraflores limestone of Bolivia (Sempere, this volume). The presence of subordinate WNW-

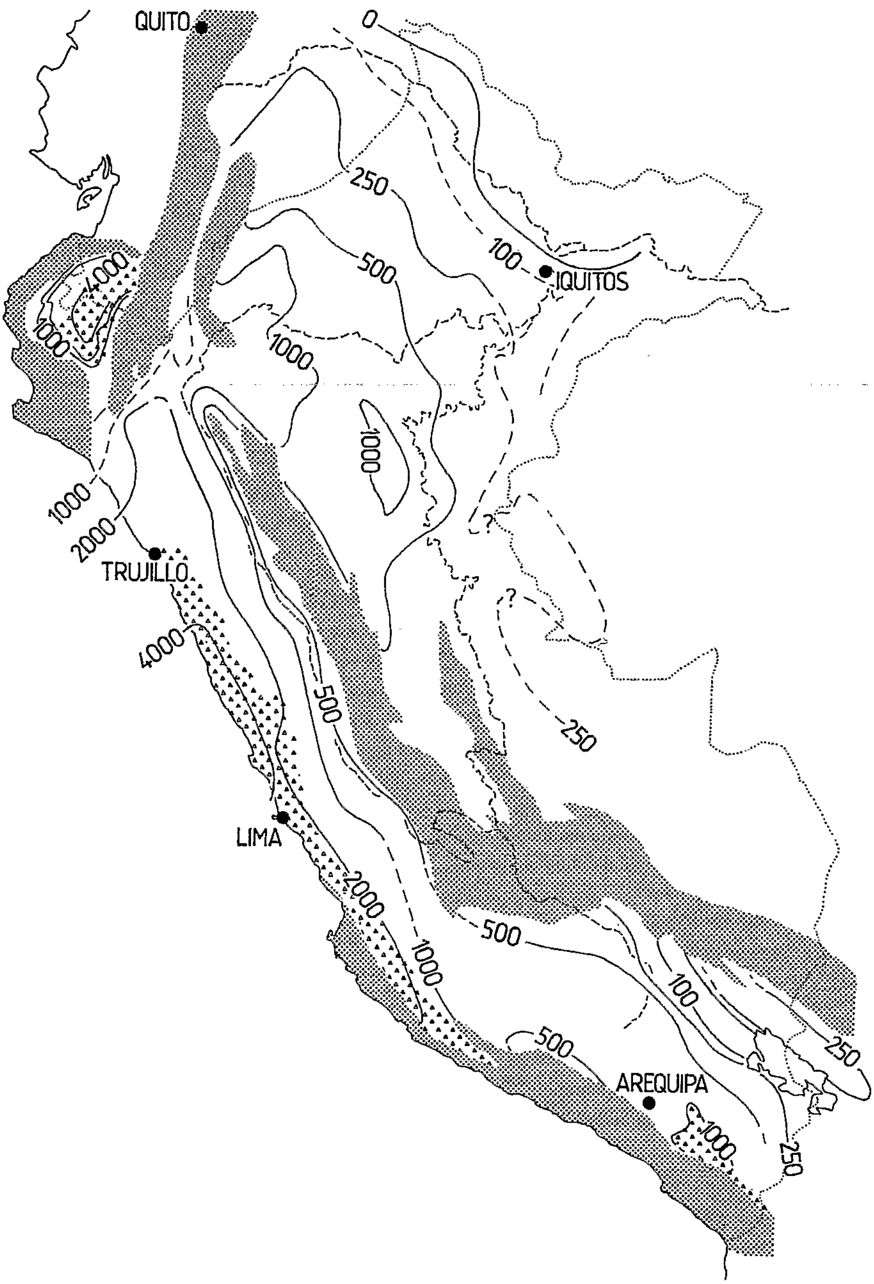

Fig. 13

Isopach map of late Aptian-late Turonian deposits. Shaded areas: no late Aptian-late Turonian deposits. Triangles: Albian-Cenomanian volcanic sequences.

trending normal faults might indicate a NE-SW tensional stress. However, scarce reverse faults (Figure 11) rather suggest a NE-SW compression, and more data would be necessary before reaching a final conclusion (Figure 12).

(Note that where the Ayavacas limestones are not capped by Cretaceous beds their chaotic aspect must be ascribed to superimposed Cretaceous and Tertiary deformations, rather than to Tertiary deformations only, as sometimes suggested (De Jong, 1974; Ellison et al., 1989).

Farther northeast, no data are available.

The Middle Cenomanian-Turonian Period

During this period a widespread marine transgression permitted the deposition of thick even carbonate shelves on most of the margin. Meanwhile, in the probably emergent coastal area, the coastal Batholith was emplaced.

Northwestern Peru, Northern Peru and Ecuador

In the Peruvian-Ecuadorian Lancones-Celica Trough, turbidite sedimentation continued to take place (Morris and Aleman, 1975, Figure 13).

In the coastal area, few radiometric data are available. However, a noticeable acidic to intermediate plutonic pulse is recorded during the Middle to Late Cenomanian (94-90 Ma, Mukasa, 1986; Soler and Bonhomme, 1990). The early intrusions of the coastal Batholith were emplaced along the western border of the Western Trough, whereas the Albian plutons were emplaced within the volcanic rocks (Mégard, 1984; Soler and Bonhomme, 1990). This suggests that a weak but real crustal shortening occurred during the Late Albian-Early Middle Cenomanian phase. The study of the joints and veins associated with these Early intrusions reveals NE-SW and NW-SE orientations, and wrenching motions seem to have continued to be important (Bussel, 1983; Bussel and Pitcher, 1985).

In the Western Trough, no synsedimentary tectonic manifestations have been observed. However, detailed studies evidence a change in the orientation of the isopach curves from NNW-SSE to WNW-ESE, and a very weak SW-proceeding detrital supply, thus suggesting minor paleogeographic changes (Jaillard, 1987). Moreover, the subsidence rate notably increased during this time-span. For instance, near Oyón, the Late Middle to Late Cenomanian limestones are 900 metres thick, thus expressing a very high sedimentation rate for this period (ca 300 m/Ma, without decompaction, Jaillard, 1987; Figure 13).

During the Early Turonian, the sea reached its maximum extent in the Eastern Basin of Peru and Ecuador and deposited fossiliferous marls (lower Chonta Formation, top of lower Napo Formation), but no tectonic features have been mentioned so far.

Southern Peru

In the coastal area, few radiometric data are available, and no plutonic event has been recorded so far.

In the Western Trough, very local NNW and ENE trending minor synsedimentary normal faults have been observed in the Turonian upper part of the Arcurquina Formation. They express a weak and probably local distensional instability.

Near the Axial Swell, and in the western part of the Eastern Basin, Turonian deposits are locally lacking, because of the paleotopography inherited from slidings of the Ayavacas limestones, or from deformation of the substratum (Figure 13). In this case, Senonian deposits disconformably overlie the often eroded or karstified Ayavacas limestones (Audebaud, 1971; Sempere, this volume). These features, however, do not indicate Middle Cenomanian or Turonian tectonic events.

Tectonic Interpretations

The Albian folding of the Casma Group was named the "Mochica" phase by Mégard (1984). We propose to extend this name to the various events recorded during the Late Aptian-Early Middle Cenomanian period.

The Late Aptian-earliest Albian Mochica 1 event (ca 110-107 Ma): Precursor tensional instability.

Evidence of a mild extensional instability, together with the scattered but frequent acidic or bimodal volcanic flows (Figure 9), indicate a tensional strain in the western part of the Peruvian continental margin. The direction of the strain is unknown. It is interpreted as a precursor event of the subsequent Albian "Mochica" deformations. The resumption of plutonic activity 113 to 111 Ma ago (Lancones-Celica and Ilo plutons) suggests a change in the subduction pattern.

The Early and Middle Albian Mochica 2 events (ca 107-100 Ma): Extension-compression in the arc or back-arc system.

In northern Peru, although most of the thick subduction-related coastal volcanic sequences yielded Mid-Albian fauna, it is possible that locally they began to overflow earlier (pre-113 Ma in the Lancones Trough). In southern Peru, their frequently disconformable basal contact suggests that the early volcanic effusions were associated with tectonic activity.

North of Lima, and as far as southwestern Ecuador (Figures 9 and 13), the thick volcanic marine flows exhibit a tholeiitic trend, and are regarded either as derived from volcanic arc activity, or as related to the opening of a marginal basin, depending on the author. In any case, the extensional setting of these very thick deposits is widely accepted, though strike-slip motions are probable. The dyke swarms recorded in the Western Trough indicate that an extensional phase occurred during Mid-Albian times. However, Early Mid-Albian (102 Ma) intrusions which cross-cut already folded rocks demonstrate that compressive pulses also occurred before this period (105 Ma?, original "Mochica" phase of Mégard, 1984). This indicates an alternation of compressive-tensional events, which can be due to the presence of strike-slip movements inducing local and/or sporadic compressions.

In contrast, south of Lima the effusive sequences are partly terrestrial and generally thinner (Figures 9 and 13). Moreover, they are generally interpreted as volcanic arcs, and have not yielded evidence so far of back-arc extension. These differences, as well as the lack of dyke swarms in the Western Trough of southern Peru, suggest first, that the Mid-Albian extensional stress was weaker than in northern Peru, and second, that the subduction regime was different.

The Late Albian-Early to Middle Cenomanian Mochica 3 phase (ca 100-94 Ma): Accretion of subduction-related volcanic centres.

In northwestern Peru, further studies are necessary, in order to specify the nature, importance and extent of the major regional tectonic event, embodied by the Late Albian-Cenomanian unconformity. However, it probably correlates with the compressional folding event responsible for the emergence of the coastal volcanic units of northern Peru. We interpret this event as the collision and accretion of deformed volcanic centres along the western edge of the continental margin.

Subsequent deformations probably modified the original geometry of the tectonic structures, and Tertiary volcanism obscured the structural relations with the present-day Western Cordillera. As a result of these poor outcropping conditions, the Mochica 3 phase has been interpreted either as a mild and relatively minor event (Mégard, 1984, 1987), or as an important tectonic phase responsible for a significant crustal shortening (Vicente, 1990). Whichever the case, it represents the earliest major compressional Cretaceous event in the Peruvian margin. Along the south Peruvian coast, no specific studies have been carried out on Mid-Cretaceous tectonic events. However, neither have any Mid-Cretaceous folds been observed so far in this area.

The N-S to NNE-SSW compression and the related E-W to WNW-ESE extension recorded in the Western Trough of central Peru apparently conflict with the expected ENE-WSW compression provoked by the closure of the NNW trending coastal basin (Figure 10). However, strong NNW-SSE to N-S dextral wrenching movements (Bussel and Pitcher, 1985) may have induced a NNE-SSW compression and a WNW-ESE extension, which could account for the observed features. These strike-slip movements together with the observed compression trend (Figure 10) suggest an oblique accretion, and a north to northeastward-trending convergence.

Whereas the coastal area of northern Peru underwent an intense continental stretching during Late Jurassic-Early Cretaceous times (Figure 13), the Albian-Cenomanian synsedimentary deformations recorded in the neighbouring Western Trough are weak (Figure 10). In contrast, these latter are important on the Axial Swell of southern Peru, whereas the Late Jurassic-Early Cretaceous crustal extension was less intense on the coast. The important slides in the Mid-Cretaceous limestones of southern Peru can be partly explained by the abundance of interbedded plastic red shales, or by their location on the possibly mobile Axial Swell. However, it is also probable that, in northern Peru, most of the Mochica shortening has been accommodated by tectonic inversion of the Albian extensional crustal structures of the coastal basin, whereas in southern Peru the paucity of such inherited extensional structures permitted transmission of the tectonic strain to the Eastern regions.

The Late Middle Cenomanian-Turonian period (ca 94-88 Ma): Tectonic remission and flexural subsidence?.

In most of the Peruvian margin this time-span is a quiescent magmatic and tectonic period. The Western Trough of northern Peru registered a noticeable increase in subsidence and sedimentation rates by Cenomanian times (Figure 13). This may be explained, if one accepts the eastward thrusting of the coastal units during the Mochica phase (Vicente, 1990), by crustal bending resulting from the thrust load. Nevertheless, the lack of structural data makes such an interpretation hypothetical. In southern Peru, the scarce and minor Late Turonian tectonic features probably represent precursors of the Senonian tectonic events.

Coniacian-Latest Campanian: The "Peruvian Phase"

Senonian times are still rather poorly understood, because they mostly gave place to unfossiliferous continental beds, and subsequent erosions have often removed part of the deposits. The progressive emergence of the Peruvian margin during the Senonian has been denominated the "Peruvian phase" (Steinmann, 1929).

The Turonian-Coniacian Boundary Event

The Turonian-Coniacian boundary is characterized by the irruption of red to brownish marine or continental shaly deposits.

Northwestern Peru, Northern Peru and Ecuador

In the Lancones-Celica Trough of northwestern Peru and southwestern Ecuador, turbiditic sedimentation continued (Morris and Aleman, 1975).
In the coastal area, Turonian and Early Santonian times (91 to 85 Ma) are marked by a striking plutonic quiescence (Beckinsale et al., 1985; Soler and Bonhomme, 1990). The tectonic regime seems to have been dominated by a high fault-slip rate, and a variable regional compression (Bussel and Pitcher, 1985).
In the Western Trough, marine Coniacian deposits conformably overlie the Turonian limestones (Celendín Formation, Benavides, 1956; Wilson, 1963; Jaillard, 1987). They are characterized by an abundant shaly and subordinate sandy detrital supply, and by a restricted depositional environment (Jaillard, 1987; Mourier et al., 1988b). In central Peru, the Celendín Formation is less calcareous and shows shallower, even tidal, depositional environments. Moreover, the 200 to 300 m-thick series deposited during the 4 to 6 Ma-long Early Senonian (Figure 14) contrast with the 1000 to 2000 m-thick limestones deposited during the 7 to 8 Ma-long Cenomanian-Turonian interval (Figure 13).
In the Eastern Basin of Peru and as far as eastern Ecuador, the Turonian limestones are capped by confined marine shales (upper Napo Formation, Tschopp, 1953; Bristow and Hoffstetter, 1977; upper Chonta Formation, Kummel, 1948; Ducloz and Rivera, 1956; Rodriguez and Chalco, 1975; Jaillard, 1987; Figure 15).

Southern Peru

Along the coast, very little is known about magmatic activity in the Batholith area.
In the Western Trough, in the Arequipa area, red shales and evaporites (Chilcane Formation) of probable Coniacian age conformably overlie the Turonian shelf limestones. South of Abancay, Coniacian deposits seem to be absent, since the Senonian continental Anta-Anta Formation disconformably overlies the Turonian limestones (Pecho, 1981).
On the Axial Swell, and in the eastern part of the Western Trough, sparse outcrops of red shales, overlying the pre-Senonian limestones, are disconformably overlain by Oligocene conglomerates, and may be tentatively ascribed to the Coniacian.
In the Eastern Basin, near the Lake Titicaca and in the Cuzco area, evaporite-bearing red shales conformably overlie the Mid-Cretaceous limestones or the undated Cotacucho sandstones (upper Yuncaypata Formation, Kalafatovitch, 1957, lower Vilquechico Formation, Jaillard et al., in press; Figure 15). In the Sicuani zone, red sands and shales (Hanchipacha Formation) unconformably overlie the deformed and partly eroded Ayavacas limestones (Audebaud, 1971, 1973). In most of the eastern area of southern Peru, the 300 to 600 m thick Coniacian-Santonian deposits (Figure 14) contrast with the much thinner (20 to 200 m) Late Aptian-Turonian series (Figure 13).

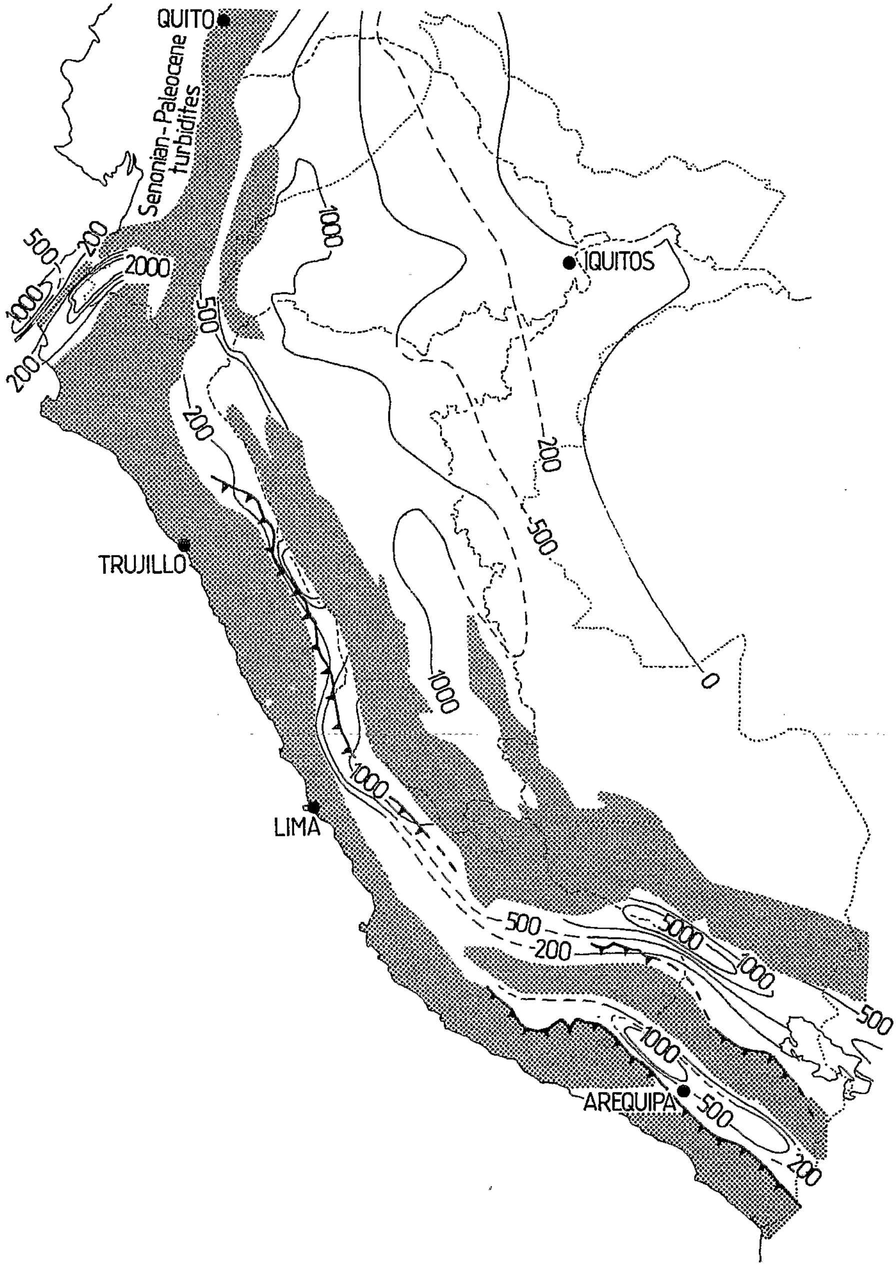

Fig. 14

Isopach map of Coniacian-Paleocene deposits, and probably active thrust faults. Shadowed areas: no Senonian-Paleocene deposits.

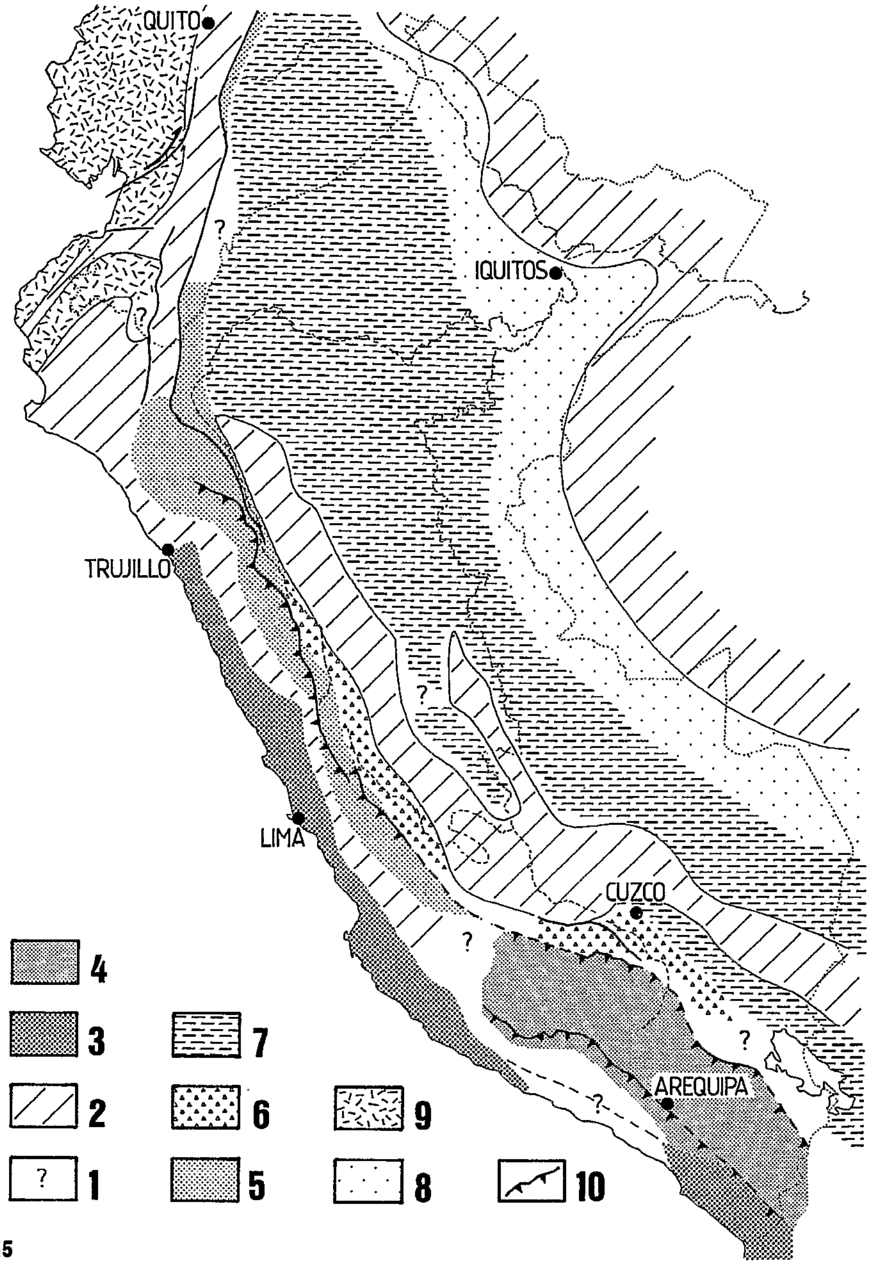

Fig. 15

Sketch map of the Senonian sedimentary facies in Peru and Eastern Ecuador. 1: No information. 2: No outcrops. 3: Emergent since Cenomanian times. 4: Emergent since the Coniacian, with a short-lived Santonian marine transgression, and with Campanian (?) foreland deposits. 5: Emergent since latest Santonian times. 6: Subsident red bed troughs of probable late Campanian-Maastrichtian age. 7: Late Campanian and Maastrichtian partly marine deposits. 8: Continental deposits throughout Senonian times. 10: Thrust faults probably active during the Senonian.

The Earliest Santonian (?) Event, and the Late Santonian-Campanian Period

This time-span is marked by the diachronous emergence of the margin, and by the beginning of compressional deformation within the western Trough.

Northwestern Peru, Northern Peru and Ecuador

In the Lancones-Celica Basin, turbiditic sedimentation continued to take place (Morris and Aleman, 1975).

Along the coast, plutonic activity resumed, with mainly granodioritic 85 to 76 Ma-old plutonic rocks (Beckinsale et al., 1985; Soler and Bonhomme, 1990). Near Chiclayo, syn-metamorphic deformation is indicated by the K-Ar 82 Ma age (Early Campanian) yielded by a foliated gabbro (Mourier, 1988).

In the Western Trough, except in its easternmost part, the top of the Celendín Formation is of Early Santonian age (Benavides, 1956; Wilson, 1963; Mégard, 1978). By Late Santonian times most of the region was emergent (Figure 15). The overlying red beds have long been considered Santonian in age (Mégard, 1978; Romani, 1982). However, their charophyte assemblages most probably indicate a Middle to Late Campanian age (Mourier et al., 1988b; Jaillard et al., 1993).

In the Eastern Basin of Peru and Ecuador, marine sedimentation prevailed until Santonian times (upper Chonta and upper Napo formations, Kummel, 1948; Tschopp, 1953; Pardo and Zuñiga, 1976). Restricted conditions are expressed by the local occurrence of black shales. The lack of any Late Santonian to Early Campanian fauna suggests the existence of a sedimentary hiatus, probably due to of the progressive uplift of the whole area.

Southern Peru.

Along the coast, after the emplacement of the Tiabaya pluton, an important plutonic gap occurred between 84 and 70 Ma (Soler et al., 1989), though a 77-80 Ar-Ar age has recently been reported in southwesternmost Peru (Clark et al., 1990).

In the Western Trough near Arequipa, the Coniacian evaporites and shales grade upward into coarsening-upward, southwestward-flooding fluvial shales and sands (lower Querque Formation, Vicente et al., 1979; Figure 16). Farther southeast, the Mid-Cretaceous volcanic Matalaque Formation is unconformably capped by a coarsening-upward sequence of SW-flooding fluvial sandstones and conglomerates which exhibits internal disconformities (lower Omoye Formation, Figure 16). These latter indicate a progressive northeasterly bending of the substratum, thus suggesting a NE-SW compression (Figure 18). In both areas, these are capped by marine limestones locally dated as Santonian (Middle Querque Formation, Hosttas, 1967; Vicente, 1981; Middle Omoye

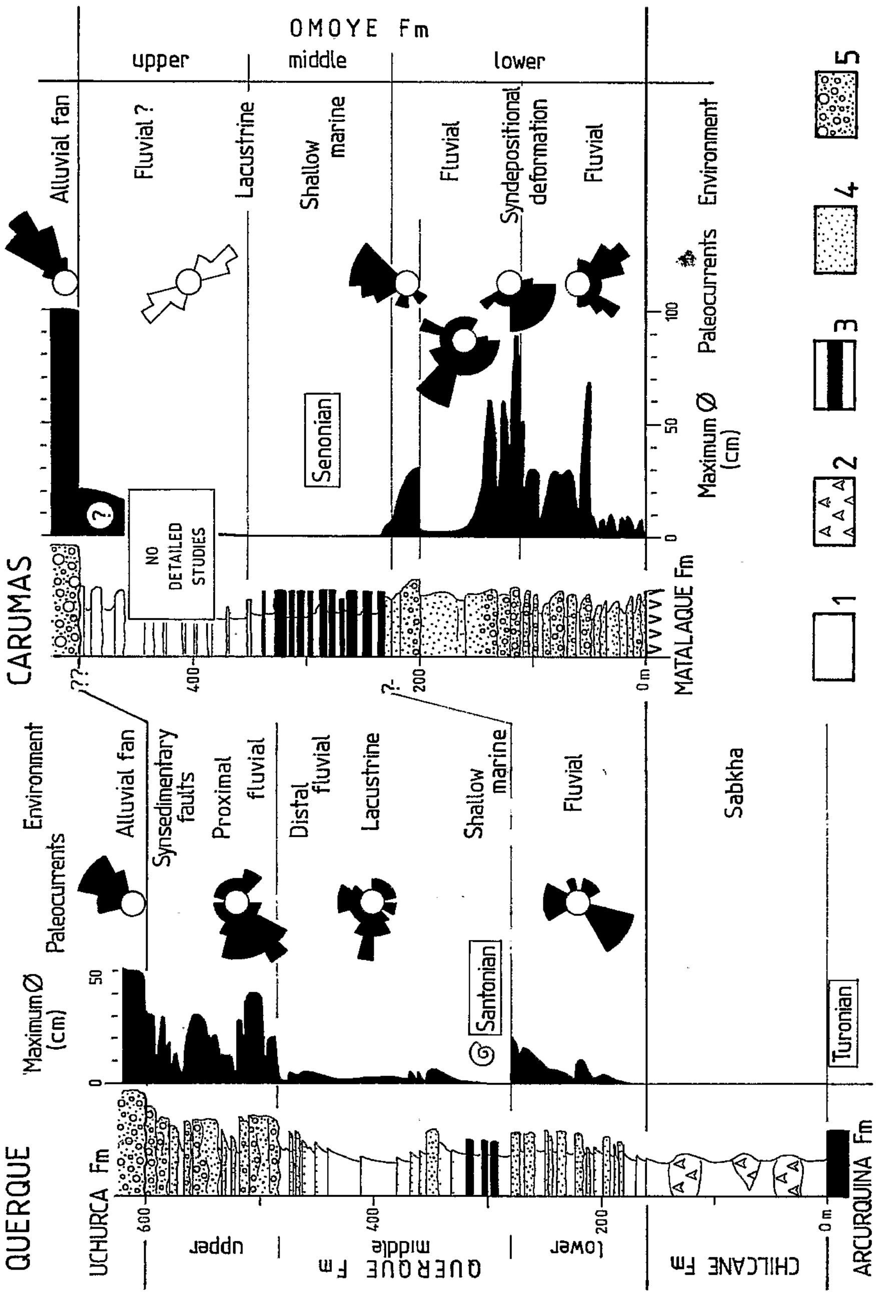

Fig. 16

Sedimentary-tectonic evolution of the Senonian deposits of the Arequipa area. 1 : Shale. 2: Gypsum. 3: Limestone. 4: Sandstone. 5: Conglomerate.

Formation, García, 1978), which probably correspond to the Early Santonian eustatic sea-level rise. They are overlain by lacustrine to fluvial coarsening-upward sequences of probably Late Santonian to Campanian age (upper Querque and upper Omoye Formation, Figure 16). Tectonic activity thus seems to have prevailed during the latest Coniacian-earliest Santonian (?), whereas the Late Santonian-Campanian time-span is a relatively quiet period, though a mild uplift suggests that compression continued.

In the eastern part of the Western Trough and on the Axial Swell, there are no known Santonian-Campanian deposits.

In the Eastern Basin, from Lake Titicaca up to the Cuzco area, shales and subordinate sands and limestones contain a well-defined marine horizon, which correlates with the Santonian transgression (lower and Middle Vilquechico Formation, Jaillard and Sempere, 1989; Jaillard et al., 1993, upper Yuncaypata Formation, Kalafatovitch, 1957; Carlotto et al., 1990; Hanchipacha Formation, Audebaud, 1973). Near Abancay, red shales and subordinate sands are also known (Anta-Anta Formation, Pecho, 1981), but their age is unsure. Farther east, in the Oriente, marine sedimentation went on till Senonian times (Dávila and Ponce de León, 1971), but marine Campanian deposits are unknown.

The Late Campanian Phase

The Late Campanian (and earliest Maastrichtian?) phase follows a quiet period, locally marked by a short-lived marine transgression of Mid-Campanian age. It probably represents the tectonic climax of the "Peruvian phase".

Northwestern Peru

In northwestern Peru, the Campanian Tablones conglomerates unconformably overlie Paleozoic to Senonian rocks (Olsson, 1944; Séranne, 1987; Morris and Aleman, 1975; Figures 14 and 15) and mark the end of turbiditic sedimentation in the western part of the Lancones Basin (Morris and Aleman, 1975). They express both the beginning of a marine transgression (Zuñiga and Cruzado, 1979; Séranne, 1987), and a noticeable uplift of the pre-Mesozoic crystalline massifs (Olsson, 1944; Morris and Aleman, 1975).

Northern Peru and Eastern Ecuador

In the coastal Batholith, a significant plutonic gap is recorded between 77 and 73 Ma (Soler and Bonhomme, 1990), and is followed by a significant magmatic pulse between 73 and 70 Ma (Beckinsale et al., 1985).

In the coastal zone, Mourier (1988) supposed that uplift continued, and that thrustings and ductile deformations occurred. However, in spite of one 82 Ma date (Mourier, 1988), the age of this deformation is actually poorly constrained (post-Turonian and pre-latest Paleocene), and at least part of it can result from the latest Paleocene Inca 1 tectonic phase.

Near the boundary between the Western and the Eastern Troughs, a short-lived Mid-Campanian marine transgression is locally recorded below the Late Campanian to Maastrichtian red beds (Mourier et al., 1988b). We may suppose that most of the continental red beds of the Western Trough are of post-Middle Campanian age. This is probably also the case with the thick red bed sequence of the Sihuas area (improperly named Chota Formation by Benavides, 1956 and Wilson et al., 1967), and of the La Oroya area, since the base of the latter contains charophytes (Mégard, 1978) similar to those yielded by the Mid-Campanian beds of northern Peru (Mourier et al., 1988b; Jaillard et al., 1993). Cretaceous foraminifera-bearing marine layers interbedded in the red beds (Mabire, 1961) could represent one of the Maastrichtian marine transgressions. They indicate that deformation had already begun at this time, since they are associated with conglomeratic beds (Mabire, 1961). In some areas, the thickness of the red bed sequence can reach as much as 3000 m, but the presence of Early Tertiary deposits is probable (Benavides, 1956; Jenks, 1961; Wilson, 1963; Mégard, 1978, Figure 14). On the Axial Swell, some plutons previously considered as Late Cretaceous are now known to be of Permian-Triassic age (Soler and Bonhomme, 1987).

In the Eastern Basin of Peru and Ecuador, the resumption of detrital sedimentation is expressed by conspicuous Late Campanian to Early Maastrichtian sandstones, which conformably overlie the Santonian marine deposits (Areniscas de Azúcar 1, Vivian and Tena formations, Tschopp, 1953; Koch and Blissenbach, 1962; Fyfe, 1962; Seminario and Guizado, 1976; Petroperú, 1989; Figure 15).

Southern Peru

No intrusions are recorded in the coastal Batholith between 78 and 70 Ma (Beckinsale et al., 1985; Soler et al., 1989).

In the Western Trough, undated coarsening-upward, southwestward-flooding fluvial sequences were deposited, probably during Late Campanian times (upper Querque Formation and upper Omoye Formation, Figure 16). A few synsedimentary minor faults indicate a NE-SW compression and a NW-SE extension. The upper Querque and Omoye formations are unconformably overlain by undated coarse-grained northeastward-flooding fanglomerates (García, 1978; Uchurca Formation, Vicente et al., 1979; Figure 16). They have been tentatively ascribed to the Early Tertiary on the basis of their abundant volcanic clasts, which would have derived from the Paleocene Toquepala Formation (Vicente et al., 1979). However, they may be alternatively interpreted as Late Cretaceous foreland deposits, related to the NE progression of the Lluta overthrust, since numerous

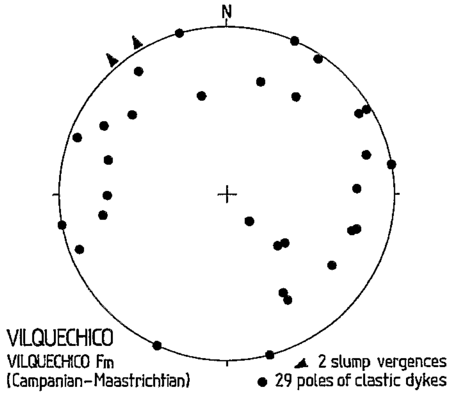

Fig. 17

Poles of clastic dykes in the middle and upper Vilquechico Formation (Middle Campanian-Late Maastrichtian).

volcanic clasts are also reported from the Late Cretaceous troughs of the Cuzco region (Noblet et al., 1987; Marocco and Noblet, 1990, see below). If this is the case, the onset of the Lluta thrust would not be of Cenomanian age (Vicente, 1990) but rather of Santonian-Campanian age (Figures 15 and 16). Nevertheless, the problem remains open, since the upper conglomerates are unfossiliferous. (Note that the contact of the Lluta thrust is intruded near Arequipa by plutons, part of which yielded Late Liassic U-Pb ages ! (188-184 Ma, Mukasa, 1986)). In the Abancay area, Late Senonian fluvial and lacustrine partly evaporitic red beds (Capas Rojas, Marocco, 1975; Anta-Anta Formation, Pecho, 1981) probably correlate with the red beds of central Peru and of the Cuzco area. On the Axial Swell, no Campanian-Maastrichtian deposits are known.

In the Eastern Basin, near Lake Titicaca, a tectonic quiescent period of probable Middle to Late Campanian age is expressed by a short-lived marine transgression (upper Middle Vilquechico Formation), and is followed by the resumption of detrital supply by latest Campanian and Early Maastrichtian times (base of upper Vilquechico Formation, Jaillard and Sempere, 1989; Jaillard et al., 1993). The orientation of open clastic dykes (Figure 17) indicates a NE to NNE-trending compressional strain, which agrees closely with the results obtained from the Cuzco and Sicuani areas. Farther northwest, the Hanchipacha Formation yielded Cretaceous marine fauna (Aptychus), and correlates with the Vilquechico Formation (Audebaud, 1973). In the Oriente region of southern Peru, the sandstones of the Vivian Formation are overlain by badly known monotonous red beds.

In the Cuzco and Sicuani areas, 4500 m-thick red bed sequences contain dinosaur tracks (San Jerónimo Group, Córdova, 1986; Noblet et al., 1987; López and Córdova, 1988). The creation of such very subsident troughs constitutes a major tectonic event of probably Late Campanian to earliest Maastrichtian age. The northward paleocurrents and the NE-SW synsedimentary compression (Figure 18) suggest that the creation and infilling of

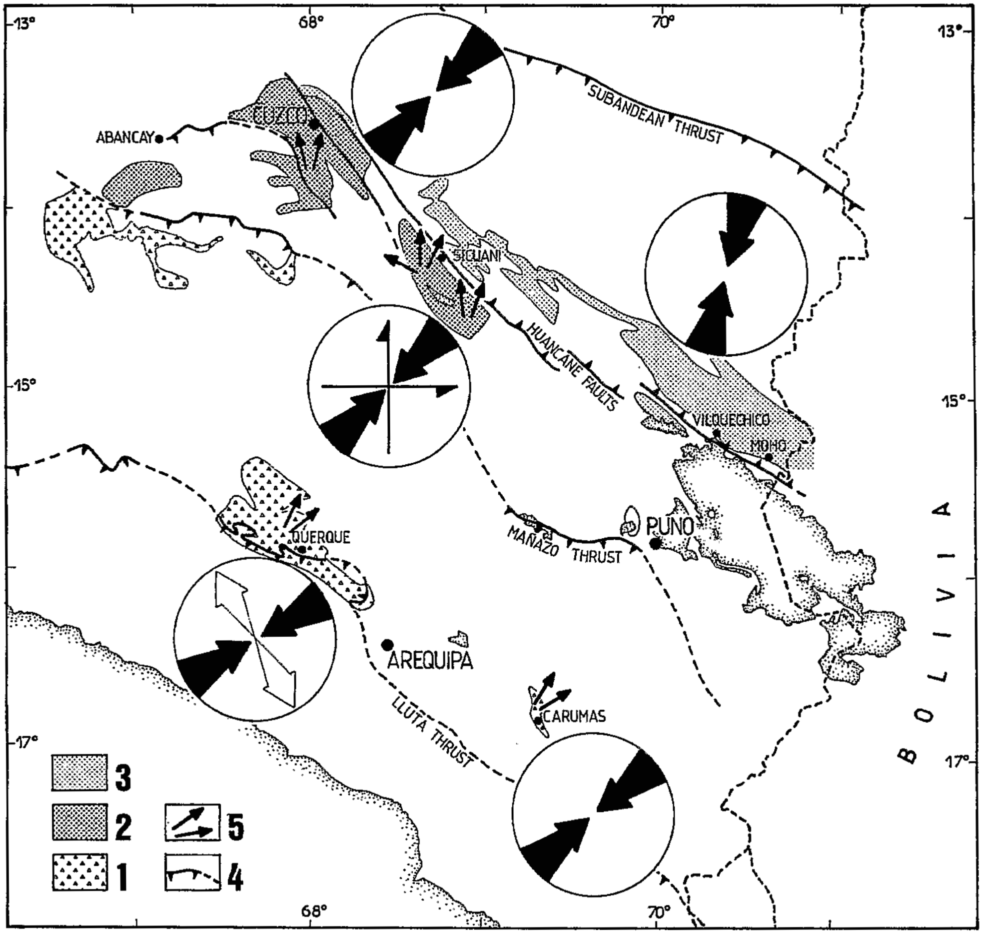

Fig. 18

Paleogeography and tectonic strain in southern Peru during Late Senonian times. 1: Western Facies: fanglomerate (of questionnable age) near Arequipa, shales and sands south of Abancay. 2: Cuzco Facies: thick fluvial red beds. 3: Eastern Facies: fine-grained, partly marine deposits. 4: Present-day major thrusts. 5: Paleocurrents.

these troughs are related to the onset of NE-trending overthrusts and to wrenching motions (Noblet, 1985; Córdova, 1986; Noblet et al., 1987; López and Córdova, 1988).

Tectonic Interpretations

During the Peruvian phase, compressional events (Turonian-Coniacian and Coniacian-Santonian boundaries, latest Campanian) alternate with relaxation episodes, which permitted marine transgressions to reach parts of the margin (Early Coniacian, Early Santonian, Middle Campanian).

The Turonian-Coniacian boundary Peruvian 1 phase (ca 89-88 Ma): Argillaceous detrital deposits, incipient coastal uplift and inversion of subsidence.

At the Turonian-Coniacian boundary, a major paleogeographic change caused the irruption of a fine-grained detrital supply over the entire margin (Sempere, this volume). The restricted environment of the Early Senonian deposits (evaporites, confined shales) suggests that the coastal area was uplifted, thus isolating the western areas from the open sea. This is supported by the emergence of southwestern Peru, by the weak subsidence of the Western Trough, and by the increasing subsidence of the Eastern Trough, giving an inverted subsidence pattern with respect to the Mid-Cretaceous (Sempere et al., 1988; Figures 13 and 14). No evidence of tectonic activity has been reported so far in the Coniacian deposits. Late Turonian and Coniacian times coincide with a striking plutonic gap in the coastal Batholith area.

The Late Coniacian-earliest Santonian Peruvian 2 phase (ca 87- 86 Ma): Incipient thrusting and progressive emergence.

In the Western Trough of southern Peru, emergence and tectonic activity are related to a NE-SW compressional strain (Figure 18). The Late Coniacian-earliest Santonian clastic sequences of the Arequipa area are interpreted as incipient foreland deposits resulting from the beginning of the Lluta overthrust, since the paleocurrents progressively rotate from SW to NW and then to the NE (Figure 16). In the Eastern Basin, the sedimentary response to the western deformations is possibly represented by the detrital deposits below the Santonian transgression.

More generally, the increasing compression of the coastal area, associated with lateral movements, caused the uplift of the margin and the progressive retreat of the sea during Late Santonian and Campanian times. The lack of Late Santonian-Campanian deposits in the eastern part of the Western Trough and near the Axial Swell can be due to incipient uplift or to subsequent erosion. This occurred earlier in southern Peru than in northern Peru, and in the western areas before the eastern ones (Figure 15). Thus, as for the Mochica phase, the response of southern Peru to compressional stress is clearly stronger and more rapid than that of the north Peruvian margin. However, the Early Campanian ductile deformation of gabbros indicate that deformation also occurred in the coastal area of Northern Peru (Mourier, 1988).

In the Arequipa area, after the (Early?) Santonian transgression, lacustrine deposits seem to correspond to a relaxation period. This is supported, in the Eastern Basin, by the deposition of fine-grained red shales and by a Middle Campanian marine transgression.

The Late Campanian Peruvian 3 phase (ca 76-73 Ma): Thrusting and foreland deposits.

In northwestern Peru, the deposition of the Tablones conglomerates indicates a marked paleogeographic change, characterized by the uplift and erosion of the Coastal Cordillera and the sinking of the coastal area, thus expressing the creation of the first Late Cretaceous forearc basin. In the coastal zone of northern Peru, uplift probably continued and thrusting and ductile deformation possibly occurred.

In southern Peru, NE-SW compressional stress clearly dominated (Figure 18). According to our interpretation, the coarse-grained deposits of the Arequipa area might represent the infilling of the foreland basins of the Lluta major thrust (Vicente et al., 1979; Vicente, 1990). Farther northeast, erosion probably occurred.

In the Western Trough (incipient Western Cordillera), the red bed basins are located just east of the western faults of the present-day Marañón and Mañazo thrust belts (Figure 14 and 15), thus strongly suggesting that they were related to the early interplay of these faults. As for the Cuzco red bed troughs (Noblet et al., 1987; López and Córdova, 1988), they are thus interpreted as the foreland basins of these incipient overthrusts (Figures 14 and 18). Moreover, their discontinuous shape (Figure 14), their very high subsidence rate, and the northward transport of the clastic supply suggest that they are pull-apart basins, and that (dextral?) wrenching movements occurred (Noblet, 1985). However, detailed studies of these basins are necessary in order to verify such a hypothesis.

Farther east, the Late Campanian (and earliest Maastrichtian?) phase is only recorded by the detrital supply, and by clastic dykes which trend normally to the NE vergence of the Lluta and Mañazo thrusts.

Maastrichtian-Paleocene

The Maastrichtian

Northwestern Peru and Southwestern Ecuador

In the Lancones-Celica Trough, the turbiditic sedimentation may have continued (Baldock, 1982). In the coastal Talara Basin, the Tablones conglomerates are overlain by marine fine-grained pro-delta deposits of Late Campanian and Maastrichtian age (Redondo Formation, Zuñiga and Cruzado, 1979; Séranne, 1987; Figure 15).

Northern Peru and Eastern Ecuador

Along the coast, the Batholith recorded a very important magmatic pulse associated with incipient strike-slip movements (72-64 Ma, Beckinsale et al., 1985; Bussel and Pitcher, 1985). With respect to the Campanian intrusions, the Maastrichtian plutons were intruded a few tens of kilometers eastward (Soler and Bonhomme, 1990). This could suggest that some shortening occurred during Late Campanian times, or that there was a change in subduction geometry.

In the Western Trough, Maastrichtian deposits might be represented by mainly fine-grained red beds (Jenks, 1961; Mabire, 1961; Mégard, 1978), since some of them yielded marine to continental Maastrichtian fauna near the transition to the eastern Basin (Bagua area, Fundo el Triunfo Formation, Mourier et al., 1988b).

In the Eastern Basin of Ecuador and Peru, Maastrichtian deposits consist of mainly continental fine-grained deposits, with thin intercalations of marine black shales (Areniscas de Azúcar 2 and 3, Cachiyacu, Huchpayacu and Tena formations, Tschopp, 1953; Koch and Blissenbach, 1962; Bristow and Hoffstetter, 1977; Petroperú, 1989; Figure 15). Ammonites have been mentioned, but their location or determination are uncertain (Rodríguez and Chalco, 1975; Vargas, 1988).

Southern Peru

In the Western Trough near Arequipa, intrusions and volcanic flows (Toquepala Formation) began to appear by Late Maastrichtian times (70-66 Ma, James et al., 1975; Beckinsale et al., 1985; Mukasa, 1986). Maastrichtian conglomerates could be represented by the Uchurca (and Jahuay) Formation (see discussion above). South of Abancay, Pecho (1981) describes fine-grained red beds which grade northward into thicker and coarser-grained red beds (Marocco, 1978).

In the Eastern Basin, fine-grained partly marine Maastrichtian shales are known in southern Peru (upper Vilquechico Formation, Dávila and Ponce de León, 1971; Jaillard et al., in press), in Bolivia, and as far south as Northern Argentina (El Molino and Yacoraite formations, Sempere et al., 1988; Marquillas and Salfity, 1988).

On the Axial Swell, mammal-bearing sandy red shales have been ascribed to the Maastrichtian (Grambast et al., 1967; Sigé, 1972). Comparable deposits have been observed in the Cuzco area, and might represent an eastern, coarser-grained equivalent of the Maastrichtian upper Vilquechico Formation (Jaillard et al., in press).

Near Cuzco and Sicuani, subsidence took place, and as much as 4500 m of coarse-grained fluvial red beds were deposited between latest Campanian and Late Maastrichtian times, as indicated by dinosaur tracks (Noblet et al., 1987; San Jerónimo Group, López and Córdova, 1989; Figure 14 and 15). The increasing abundance of volcanic clasts is regarded as indicating the presence and increasing erosion of a southern coeval volcanic arc (Marocco and Noblet, 1990), which could be the Toquepala system. Farther south, the emplacement of the Andahuaylas-Yauri pluton may have begun (Soler et al., 1989).

The Paleocene

Northwestern Peru, Northern Peru and Eastern Ecuador

The Talara Basin received a marine fine-grained (black shales) sedimentation (Séranne, 1987).

Along the coast, a noticeable plutonic event occurred during Early Paleocene times, but it rapidly vanished, and no intrusions are known between 60 and 54 Ma (Beckinsale et al., 1985; Soler and Bonhomme, 1990). High fault slip-rate and regional compression are recorded between 68 and 64 Ma (Bussel and Pitcher, 1985).

In the Western Cordillera (formerly Western Trough), the presence of Paleocene deposits is assumed in medium-grained fluvial red beds (Jenks, 1961; Wilson, 1963; Mégard, 1978), but no reliable stratigraphic data is available at present.

In the Eastern Basin of northern Peru, at the boundary with the Western Trough, Paleocene deposits are lacking (Mourier et al., 1988b; Naeser et al., 1991). In the Oriente of Ecuador, Paleocene deposits seem to be reduced or even absent beneath the unconformable Late Paleocene-Eocene sandstones and conglomerates (Tschopp, 1953; Bristow and Hoffstetter, 1977; Baldock, 1982). Farther southeast, the Paleocene is poorly characterized. Fine-grained red shales and silts with brackish intercalations (evaporites and marls) are ascribed to this stage (Sol and Yahuarango formations, Koch and Blissenbach, 1962; Fyfe, 1962; Feist et al., 1989; Petroperú, 1989).

Southern Peru

Along the coast and in the western part of the Western Cordillera (ex-Western Trough), numerous magmatic effusions and intrusions took place (Toquepala system, Beckinsale et al., 1985), recording a climax near the Danian-Thanetian boundary (57-62 Ma; Laughlin et al., 1968; Stewart et al., 1974; Bellon and Lefèvre, 1976; Vatin-Pérignon et al., 1982; Beckinsale et al., 1985; Clark et al., 1990). According to Bussel and Pitcher (1985), the compressive event recorded farther north is poorly expressed in southern Peru. In the rest of the western domain, no Paleocene deposits are recorded.

In the Eastern Basin, the Vilquechico Formation is conformably overlain by a few tens of meters of shales. This continental series of purple shales and thin-bedded sandstones becomes much thicker in Bolivia (Santa Lucía and Impora formations, Sempere, this volume), and farther northwest (Chilca Formation of the Sicuani area, Audebaud, 1973), where it yielded Paleocene fossils (Gayet et al., in press; Mourier et al., 1988). In the

Cuzco area, some hundreds of meters of fine-grained red shales overlie the Cretaceous deposits (base of Punacancha Formation, López and Córdova, 1988) and are followed by 2000 m of undated fluvial conglomerates (Punacancha Formation, Córdova, 1986; López and Córdova, 1988; Figure 14). In the Oriente of southern Peru, undated red beds were deposited. According to Soler et al. (1989), the Andahuaylas-Yauri batholith must have been formed at that time.

The Paleocene-Eocene Boundary Phase

This event closes the marine evolution of the Peruvian margin. It is marked throughout the margin by disconformable coarse-grained deposits, which often post-date tectonic deformations.

Northwestern Peru, Northern Peru and Eastern Ecuador

In the Talara basin, the Basal Salinas sands and conglomerates disconformably overlie the marine Paleocene shales (Marsaglia and Carozzi, 1990), and grade upward into Eocene fluviodeltaic sandstones (Séranne, 1987).

On the coast of central Peru, a conspicuous magmatic gap occurred between 54 and 50 Ma (Beckinsale et al., 1985; Soler and Bonhomme, 1990).

In the Western Cordillera of northern Peru, volcanic strata unconformably overlie folded sediments (Wilson, 1975), and fanglomerates interbedded with 49-50 Ma volcanic layers post-date a folding phase (Noble et al., 1990). Farther east, Maastrichtian red beds are disconformably capped by fluvial conglomerates associated with a 54 Ma tuff (Rentema Formation, Naeser et al., 1991).

In the Eastern Basin of Peru and Ecuador, the Paleocene or Cretaceous deposits are often disconformably overlain by Late Paleocene-Early Eocene sandstones and conglomerates (Tiyuyacu and Cuzutca formations, Tschopp, 1953; Koch and Blissenbach, 1962; Bristow and Hoffstetter, 1977; Basal Pozo Formation, Petroperú, 1989).

Southern Peru

Near the coast, the Toquepala magmatism ceased by 60 Ma, but hydrothermal phenomenae are then recorded during the Early Eocene (52 Ma K-Ar and Ar-Ar ages, Clark et al., 1990), and are possibly later than the tectonic phase. In the Western Cordillera, no information is available so far.

In the Eastern Basin, the Eocene fluvial conglomerates of the Muñani Formation (Audebaud et al., 1976; Feist et al., 1989) disconformably overlie the Maastrichtian upper Vilquechico Formation. Near Cuzco, the basal contact of the mainly volcaniclastic coarse-grained conglomerates of the upper Punacancha Formation (Córdova, 1986) could represent the discontinuity of the Paleocene-Eocene boundary.

Tectonic Interpretations

The Maastrichtian (ca 73-66 Ma): Tectonic remission, marine transgression and magmatic pulse.

The red bed sedimentation of the Western areas proceeds from erosion of the formerly created reliefs, but the lack of important sedimentary discontinuities indicates a rather stable tectonic regime. However, the very subsident basins of the Cuzco area suggest that continuous tectonic processes went on locally (Figure 14). This relative tectonic relaxation permitted a widespread marine transgression to invade the eastern parts of the entire central Andean margin and to deposit very homogeneous sediments (Figure 15). This non-compressive period favoured the occurrence of a significant magmatic pulse along the coast.

The Paleocene (ca 66-56 Ma): Reduced sedimentation and volcanic pulse.

During Paleocene times, the western areas and the western parts of the Eastern Basin recorded a reduced sedimentation or even a stratigraphic gap (northeastern Peru, Ecuador, Titicaca area), whereas the more easterly zones (eastern Peru, Bolivia) received rather thick red bed deposits. The latter exhibit a roughly coarsening-upward evolution (Sempere, this volume). Though no clear tectonic event can be identified, these features can be regarded as resulting from the resumption of a continuous mild compressional uplift of the Western Areas, responsible for the erosion or reduced sedimentation recorded in the western parts of the Eastern Area. After 60 Ma (Danian-Thanetian boundary), the disappearance of the intrusions in northern Peru and of the Toquepala volcanism of southern Peru could be related to the increasing compressional strain.

The Paleocene-Eocene boundary Inca 1 phase (ca 55-53 Ma): The first Tertiary Andean phase.

The study of this phase is beyond the scope of this paper. It has only recently been identified in Peru, and its tectonic manifestations are still poorly documented. However, the irruption of unconformable widespread coarse-grained deposits, the uplift indicated by the change from marine shales to deltaic sands in the Talara basin, and local folding events express the importance of this tectonic phase, which is interpreted as the earliest well-defined Tertiary compressional phase of the central Andean margin.

Relationships with Geodynamic and Magmatic Events

Relationships between Tectonic Phases and Geodynamic Events

Three main tectonic periods can be recognized during the Kimmeridgian-Paleocene interval (Figure 19). We propose the name "Virú period" for the Kimmeridgian-Berriasian events. They are followed by the Early Albian-Early Middle Cenomanian "Mochica period", and the Early Coniacian-earliest Maastrichtian "Peruvian period". They are separated by periods of tectonic quiescence or relaxation. As no pre-Late Cretaceous plate reconstructions are available, the Kimmeridgian-Berriasian period will be analyzed separately.

The Kimmeridgian-Berriasian "Virú Period" (145-130 Ma)

It can be divided into three discrete phases. The Kimmeridgian event mostly affects southern Peru, and seems to be related to the Araucan phase of Argentina and Chile. The Tithonian phase is best regarded as a consequence of the collision of allochthonous terranes and the subsequent folding and thrusting of the western border of the Ecuadorian margin. The Berriasian event could be due to a general uplift originated in the east, and related to South Atlantic rifting. Since the location and origin of these events are quite separate, they can be ascribed either to a unique cause differently expressed because of local parameters (inherited tectonic features, heterogeneous structure of the crust, etc.), or to separate and independent geodynamic factors. The varied nature of these tectonic events supports the latter hypothesis, though interactions with local parameters are possible.

In most of the oceanic spreading centres of the world, Kimmeridgian-Tithonian times (145-140 Ma) are marked by a sharp decrease in the accretion rates (Olivet et al., 1984; Klitgord and Schouten, 1986; Savostin et al., 1986). These ridges still belong to the roughly E-W-trending Tethyan system, and it can be supposed that the NE-trending hypothetical Colombian-Tethyan ridge (Mooney, 1980) recorded the same sharp decrease in the accretion rate (Jaillard et al., 1990). Combining models proposed by Duncan and Hargraves (1984) and Aspden et al. (1987); Jaillard et al. (1990) proposed that, along the Peruvian margin, the roughly southeastward convergence induced by spreading activity of the Tethyan oceanic ridges would have been replaced by a roughly northeastward convergence induced by Pacific spreading centres after Kimmeridgian times. This model would explain the appearance of a Tithonian subduction-related volcanic system along the Peruvian margin, and the coeval dextral accretion of south-proceeding terranes along the Ecuadorian-Colombian margin (Mourier et al., 1988; Aspden et al., 1988).

Meanwhile, the rifting of the roughly N-S trending southern South Atlantic ocean began (147-136 Ma, Ojeda, 1982; Sibuet et al., 1985). Although it is still difficult to separate the role of both geodynamic events in the tectonic phases recorded in the Peruvian margin, they indicate that Kimmeridgian-Tithonian times mark the end of the Tethyan-dominant regime, and their replacement by an Atlantic-PaleoPacific (Farallón)-dominant system.

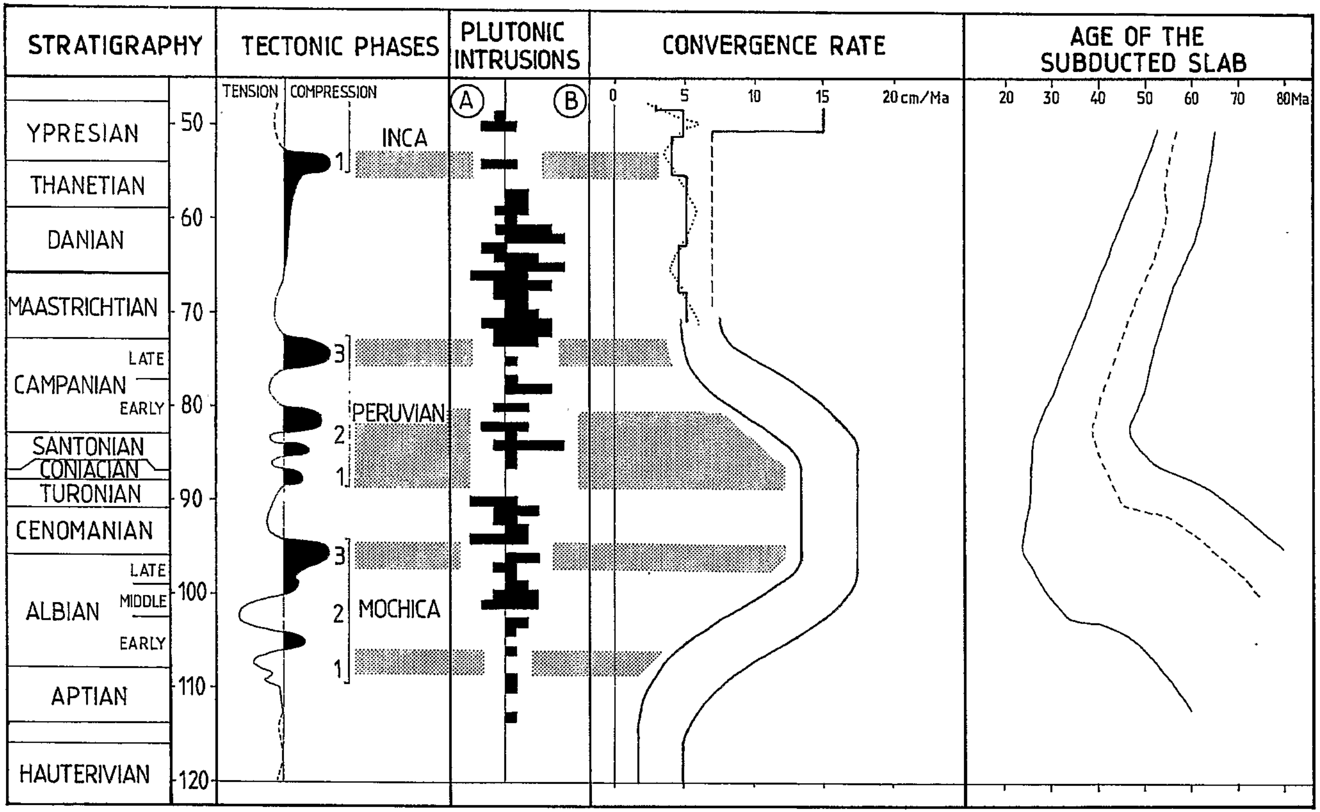

Fig. 19

Relations between tectonic events, magmatic pulses and Plate geodynamics, in the Peruvian margin, between Hauterivian and Paleocene times. Plutonic intrusions: A: On the coast of central Peru (after Soler and Bonhomme, 1990). B: Throughout the whole of coastal Peru (after Beckinsale et al., 1985; Mukasa, 1986). Convergence rate between the Farallón and the South American plates and relative age of the subducted slab (after Soler and Bonhomme, 1990).

By Berriasian times, the southern South Atlantic ocean began to open (135-130 Ma, Rabinowitz and La Brecque, 1979; Goodlad et al., 1982; Scotese et al., 1988). The coeval events (mainly uplift) of the Peruvian margin and the subsequent arrival of east-deriving mature sandstones (Valanginian) can therefore be ascribed to the rifting processes (doming?) affecting the northern South Atlantic ocean. The stable tectonic regime observed during most of Early Cretaceous times in Peru coincides with a spreading quiescence observed in the South Atlantic, before the opening of its northern segment by Late Aptian-Albian times (Lehner and De Ruiter, 1977; Rabinowitz and La Brecque, 1979).

The Middle and Late Cretaceous "Mochica" and "Peruvian" Periods (108-95 and 88-73 Ma)

Both phases will be analyzed together in this section, and compared with geodynamic events.

In a subduction setting, compressive stress in the upper plate is classically attributed to various independant factors which are (1) the young age of the subducted slab, which is then buoyant and induces a low-dipping subduction angle; (2) the subduction of oceanic obstacles; (3) the high convergence velocity of the subducted oceanic slab; and (4) the high absolute displacement rate of the overriding plate toward the trench (see Uyeda and Kanamori, 1979; Uyeda, 1982; Cross and Pilger, 1982; Mitrovica et al., 1989; Soler and Bonhomme, 1990).

Relationship with the age of the subducted plate

In spite of broad uncertainties in the Plate motion reconstructions for this period, the age of the subducted oceanic slab is known to have rapidly decreased between 115 and 100 Ma, to have been young (30 to 50 Ma) between Albian and Santonian times (100-80 Ma), and then to have progressively increased (40 to 65 Ma) during the Late Senonian and Paleocene (Soler et al., 1989; Soler and Bonhomme, 1990; Figure 19). Thus, the age of the oceanic lithosphere apparently cannot be directly brought in to explain the progressive increase of compressive deformation of the Peruvian continental margin during Late Cretaceous times (Soler and Bonhomme, 1990). Still less can it be used to explain the individual short-lived tectonic phases recorded by the Peruvian margin. However, the Mochica and Peruvian periods, as a whole, are coeval with the subduction of a rather young oceanic lithosphere, and these tectonic phases could be related to this long-term situation.

Relationship with convergence rates

During Middle Cretaceous to Paleocene times, the convergence rate along the Peruvian trench was in turn slow (Early Cretaceous), fast (Middle Cretaceous and Early Senonian), and slow again (Late Senonian and Paleocene)(Soler and Bonhomme, 1990). The period of fast convergence broadly correlates with two main periods of tectonic instability along the Peruvian margin, and the slow convergence periods coincide roughly with quieter intervals. Nevertheless, these correlations are unsatisfactory, since the high convergence period also includes extension or relaxation phases, and low convergence intervals include major compressive events (Peruvian 2 and 3, Incaic 1). In contrast, most of the tectonic events recorded in the Peruvian margin correlate closely with changes in the convergence rates (Mochica 1 and 3, Peruvian 2 and 3, Inca 1, Figure 19). So although high convergence rate periods broadly correlate with long-term compressive periods, the acceleration or deceleration of the convergent motion appear to be the greater determining factors in the generation of tectonic phases within the overriding continental plate. However, this observation is weakened by uncertainty with regard to stratigraphic data and plate motion reconstruction, especially during the Mid-Cretaceous quiet magnetic period.

Relationship with obliquity of convergence

Bussel and Pitcher (1985) emphasized the importance of strike-slip motions along the Peruvian coast during the Late Albian-Santonian (98-82 Ma) and the Early Paleocene (Danian, 68-64 Ma) periods. More recently (Soler, 1991a and b) proposed that strike-slip motions played a major part in the generation of the Mid-Albian to Early Cenomanian volcanic centers (see below). For the latest Cretaceous-Paleocene period, a strong dextral component along the Peruvian coast can be explained by the very oblique convergence of the Farallón oceanic plate, since the northward displacement of the latter was nearly parallel to the Peruvian continental margin (Pilger, 1984; Gordon and Jurdy, 1986; Pardo-Casas and Molnar, 1987; Mayes et al., 1990). This situation could also account for the pull-apart nature suggested for the Late Senonian red bed troughs (Noblet, 1985). If so, oblique oceanic subduction may largely have influenced the Middle and Late Cretaceous evolution of the Peruvian margin. Moreover, the change of rotation poles in plate motion can explain some of the short-lived tectonic phases, but no precise geometric reconstructions of the Pacific Plate are available for Middle and Early Late Cretaceous times.

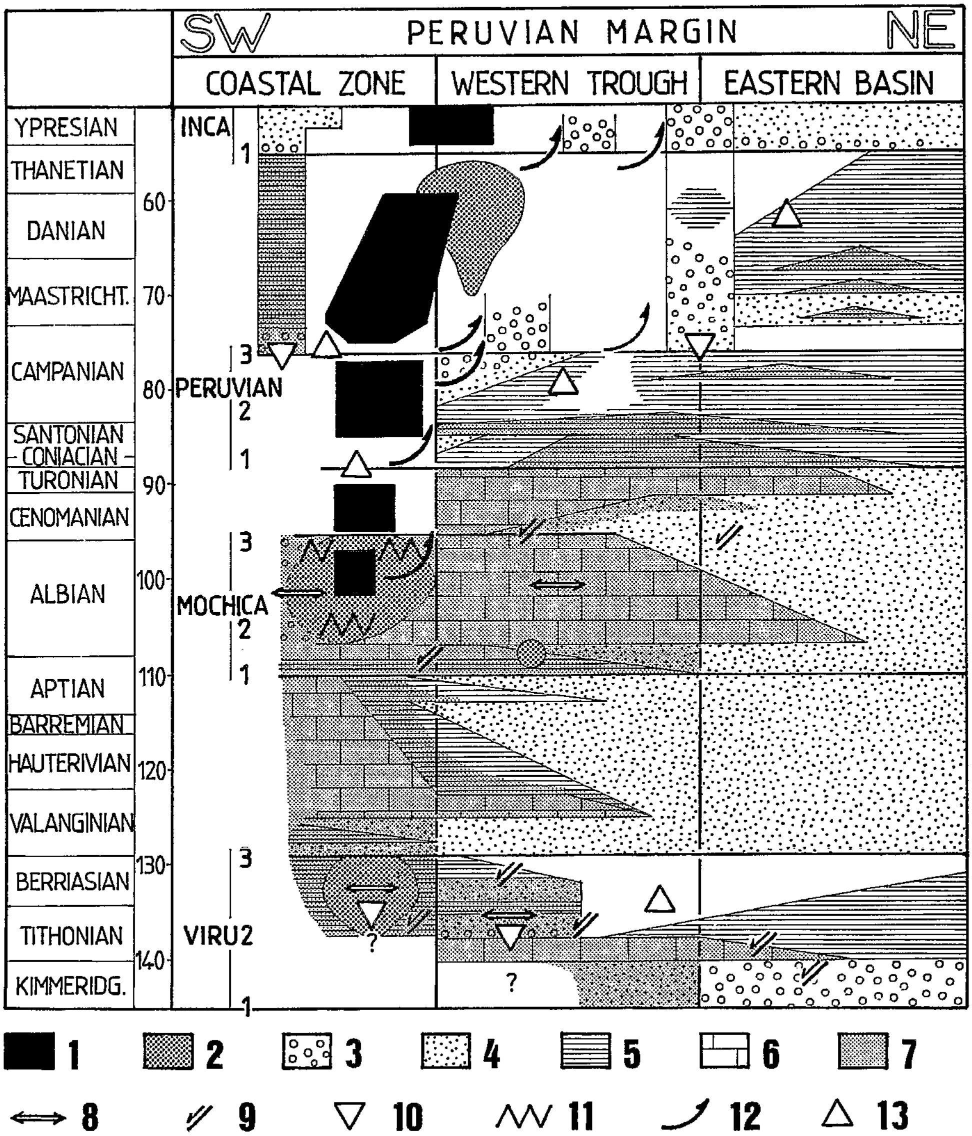

Fig. 20

Synopsis of the main tectonic-sedimentary and volcanic events of the Peruvian margin between Kimmeridgian and Paleocene times. 1: Intrusion. 2: Volcanism. 3: Conglomerate. 4: Sandstone. 5: Shale. 6: Limestone. 7: Marine deposits. 8: Extension. 9: Normal fault. 10: Tectonic subsidence. 11: Folding. 12: Thrusting. 13: Tectonic uplift.

Relationship between Tectonic Phases and Magmatism

In central Peru, Soler and Bonhomme (1990) identified four plutonic gaps in the Batholith emplacement (Figures 19 and 20). Such plutonic gaps are classically related either to compressive tectonic stress within the upper plate, which closes the crustal fractures channelling the magma (e.g. terrane accretion, Raymond and Swanson, 1980), or to the disappearance of the upper plate lithospheric wedge, which prevents magma generation. The latter situation occurs when oceanic obstacles are subducted (Nur and Ben Avraham, 1982), and/or when the oceanic slab possesses a low subduction angle.

Middle Albian times are characterized by both an extensional regime in the margin, and an intense volcanic activity in the arc-marginal basin system.

The first plutonic gap (97-94 Ma, latest Albian-Middle Cenomanian; Figure 19) coincides exactly with the Mochica 3 major phase, as recorded by the synsedimentary features in the Western Trough. It is followed by a plutonic pulse contemporaneous with the quiet Middle to Late Cenomanian period.

The second plutonic gap (90-84 Ma), more surprisingly, correlates both with a tectonic quiescent period (latest Cenomanian-Turonian) and with the beginning of the compressive Peruvian phase (Coniacian-Santonian). It is followed by a minor magmatic pulse of Early Campanian age (84-80 Ma), which correlates with the relatively quiescent interval between the Peruvian 2 and 3 events.

The third magmatic gap (80-73 Ma, Campanian, Figure 19) coincides with the Peruvian 3 major phase. A last plutonic and volcanic pulse (73-60 Ma) occurred during the Maastrichtian-Danian tectonic remission.

Finally, a plutonic gap, occurring between 60 and 54 Ma (Late Paleocene), corresponds to the incipient compression which culminated during the Incaic 1 phase of the Paleocene-Eocene boundary.

Such periods are also more or less apparent when compared with the radiometric data of the whole of coastal Peru (Figure 19). Thus, except for the latest Cenomanian-Coniacian period, the plutonic gaps broadly correlate with main compressive tectonic events.

No accretion of allochthonous terrane occurred along the Peruvian margin during Cretaceous times (Mégard, 1987; Beck, 1988). Moreover, Soler and Bonhomme (1990) assumed a rather steep-dipping angle of the subducted oceanic slab during Cretaceous times. Thus, the plutonic gaps must be due either to the subduction of oceanic obstacles, as assumed by Soler et al. (1989) for the Late Santonian-Early Maastrichtian interval in southern Peru, or, more generally, to compressive stress within the South American continental plate, the cause of which remains to be discussed.

A Tectonic-Geodynamic Model for the Cretaceous Andean Margin

In order to simplify comprehension, the Kimmeridgian-Paleocene evolution of the Peruvian margin can be divided into two major periods, separated by a period in which the general tectonic regime was inverted.

During the first period (Late Jurassic-Early Cretaceous), the Peruvian margin was dominated by an extensional regime, and from trench to continent reveals: (1) a possible forearc system, now disappeared; (2) a mainly effusive magmatic arc, the existence of which is now mostly attested to by its reworked products; (3) discontinuous marine or continental extensional basins filled both by autochthonous volcanic flows and by reworked volcanic products, which are interpreted either as ensialic marginal basins or as pull-apart basins located within the volcanic arc; (4) a mobile external margin, dominated by an extensional tectonic regime and by marine shelf deposits, and (5) a stable pericratonic internal margin, which underwent little subsidence and received mainly terrigenous sedimentation.

Such a margin pattern is classically related to an extensional margin submitted to the slow steep-dipping subduction of an old oceanic crust ("Mariana-type" of Uyeda and Kanamori, 1979; Uyeda, 1982).

During the second period (Late Cretaceous-Paleocene), the Peruvian margin underwent a northeastward propagating compressional strain, and is characterized by the following structures from the trench to the craton: (1) incipient marine to continental forearc basins; (2) a mainly intrusive emergent magmatic arc, incorporated into the deforming active margin; (3) an active thrust and fold belt, with sparse intermountain basins; (4) a belt of foreland basins; (5) a mobile zone, submitted to partly marine fine-grained detrital sedimentation and incipient compressional strain.

This pattern characterizes compressional margins submitted to the fast, low-dipping subduction of a young oceanic crust ("Chilean-type" of Uyeda and Kanamori, 1979; Uyeda, 1982).

Age of the Extensional and Compressional Periods

Extensional Period

The nature of the Kimmeridgian event is not well understood in the Peruvian margin. However, it is clearly associated with the play of normal faults in southern Peru. Extensional stress is then shown during the Tithonian phase by the opening of turbiditic and "within-arc" or "back-arc" basins and by structural analysis. Though the Berriasian event seems also to be related to Atlantic rifting, the existence of an extensional regime is suggested by the SW paleoslope incline and by the high subsidence rate of the Western Trough during Valanginian times. This situation then prevailed during Early Cretaceous

times, as shown by the noticeably differential subsidence registered on the north Peruvian margin.
The mostly extensional Virú tectonic period can therefore be regarded as a prelude to the tensional regime which was dominant during the Early Cretaceous.

Compressional Period

The beginning of compression is classically thought to be of Senonian age (ca 80 Ma, Peruvian phase) in the central Andean margin (Steinmann, 1929; Benavides, 1956; Mégard, 1978). However, the part played by the Mochica phase has recently been emphasized (Cobbing et al., 1981; Mégard, 1984; Jaillard and Sempere, 1989).
The Eastern Basin had undergone subsidence by Early Senonian times, and began to be uplifted in the Late Campanian, and more generally in Paleocene times (Figure 20). The beginning of compression there is of Late Senonian age, and roughly coincides with the Peruvian 3 phase.
In the Western Trough, the transition from subsidence to uplift took place between Turonian and Coniacian times, and the onset of syntectonic deposition is of earliest Santonian to Late Campanian age from the Southwest to the Northeast (Figure 20), expressing a clearly compressive regime (Figure 18). The beginning of compression in this region is therefore of Early Senonian age, and roughly coincides with the Peruvian 1 and 2 phases.
In the Coastal Zone, extension is thought to have been dominant during the Early Cretaceous; whereas compression began during the Early Albian, and clearly prevailed in the Late Albian and Early Middle Cenomanian (Figure 20).
Initial compression was therefore diachronous throughout the margin, and clearly began earlier toward the trench. Extrapolating these observations we may suppose that, at the trench itself, the transition from extensional to compressional stress must have occurred in the Late Aptian (ca 110 Ma), since it coincides with: (1) the arrival of a younger oceanic lithosphere in the trench; (2) the acceleration of the convergence rate (Figure 19); (3) the beginning of the oceanic accretion in the Northern South Atlantic, which led to the westward shift of the South American plate. If so, the actual beginning of compression in the Peruvian margin cannot be considered as of Senonian age. Interpretations of the consequences of this supposed Aptian-Albian compressional regime depend on the nature of the volcanic centres.

The Mochica Period

Opening and Closing of a Middle Cretaceous Marginal Basin? ...

Atherton et al. (1983, 1985) and Aguirre and Offler (1985) have suggested that the Tithonian-Berriasian and Albian volcanic centres must have belonged to the same back-arc extensional system. According to these authors, they probably represent aborted "ensialic" marginal basins, floored by continental crust. More recently, Atherton (1990) suggested that a true ocean-floored marginal basin, somewhat comparable to that of Patagonia (Dalziel et al., 1974; Aberg et al., 1984), developed in Northern Peru during Albian times. In these hypotheses, an extensional regime was dominant during Late Aptian-Middle Albian times. The marginal basin was created by crustal extensional stretching during Late Aptian or Early Albian times (Mochica 1 phase), and functioned and widened during the Middle Albian, thus explaining the high observed geothermal gradient and metamorphic pattern (Aguirre et al., 1989). Its closure occurred during Late Albian to Early Cenomanian times (Mochica 3 phase), and was associated with noticeable dextral motions (Bussel, 1983). If so, the early Mochica tectonic period would represent the time-span necessary for the trench to shift northeastward and reach the border of the continental margin proper.

This hypothesis is in keeping with the geological facts observed in the Western Trough, and has been adopted by most authors during the past few years (e.g. Mégard, 1987; Jaillard, 1987).

It remains difficult, however, to explain the compressive deformations observed during Early Albian times (105 Ma folding phase, Wilson, 1975, Mochica 2 phase), since an extensional tectonic regime is presumed to have existed at this time, and this would appear to contradict the geodynamic data, which seem to indicate a prevailing compressive tectonic regime after Late Aptian times. It would have been more likely for such a marginal basin to have opened during Early Cretaceous times, as a result of the oceanward shift of the trench-arc system, triggered by the continuous extensional regime. Moreover, in this hypothesis, it is difficult to explain why only the marginal basin is presently preserved, whereas no remnants of the volcanic arc are observed.

... Or Wrenching of a Pulled-Apart Volcanic Arc?

In contrast to the preceding hypothesis, Soler (1991a, 1991b), using the same geochemical data, in addition to some new findings, proposed that the whole range of volcanic and volcaniclastic formations could represent the remains and/or the products of the volcanic arc itself. The latter would have been active during Tithonian-Berriasian times, and then quiescent during most of the Early Cretaceous. After Late Aptian-Early Albian times, volcanic activity would have resumed, due to the new geodynamic pattern, and the volcanic arc would have been submitted to intense dextral strike-slip motions. This would explain the sporadic compressional deformation and the creation of the northern troughs filled by thick volcanic-derived products (Casma Group and Lancones Formation), these being interpreted as extensional pull-apart basins. This interpretation implies that oceanic convergence occurred toward the North, obliquely to the margin, during Albian times.

Such an interpretation of a pulled-apart volcanic arc is in agreement with the calc-alkaline geochemistry of the south Peruvian volcanic centres (Copara and Matalaque formations), as well as with the discontinuous shape of the volcanic belt (Figures 9 and 13). Moreover, the supposed northward convergence closely agrees with the compression direction registered during the Mochica phase on the Peruvian margin (Figure 10). In this hypothesis, the incipient compression would have been accommodated during the early Mochica period, by lateral displacements and wrenching deformations along the very edge of the continental margin.

Whichever the Case

The shift of the trench was achieved by the Late Albian, and culminated in the accretion of the volcanic arc or the remnants of the marginal basin with the Andean continental margin (latest Albian-Early Middle Cenomanian, Mochica 3 phase). It is worth noting that foldings and thrustings only involved the coastal zone during the Mochica period.

Though detailed geochemical and mineralogical studies have been carried out on these formations, their interpretation seems to remain debatable. Moreover, except in some areas (Myers, 1980; Webb, 1976), their overall lithologic and geometric features are so far poorly known, and further geologic surveys, as well as stratigraphic and structural field work are necessary before any conclusion can be reached.

The Peruvian Period

The Western Trough had undergone a strong crustal stretching by latest Jurassic-earliest Cretaceous times, and this controlled the Early Cretaceous subsidence (Jaillard, 1990). After the Cenomanian-Turonian quiescent period, the continental margin itself began to accommodate the ongoing compression, and the Mochica suture played again, while the extensional paleogeographic structures of the Western Trough began to invert.

The Turonian-Coniacian Peruvian 1 event seems to correspond to the re-utilization of the Cenomanian Mochica suture (uplift of the coastal zone). The Late Coniacian-earliest Santonian Peruvian 2 phase, materialized by the onset of the Lluta thrust of the Arequipa area, corresponds to the structural inversion of the southwestern border of the Western Trough. Finally, the Late Campanian Peruvian 3 phase, expressed by the creation of the red bed foreland basins, can be interpreted as the structural inversion of the northeastern border of the Western Trough (Figures 15 and 18). Therefore, the "Peruvian period" can be considered a period of tectonic inversion of the Western Trough extensional structures.

Because the westernmost areas were probably already partly inverted by the Mochica phase, and since southern Peru underwent a lesser amount of Mesozoic extension than northern Peru, the western and southern areas of the margin reacted and emerged earlier.

Conclusions

Tectonic Evolution of the Peruvian Margin

Detailed studies of the tectonic-sedimentary evolution of the Peruvian margin between Kimmeridgian and Paleocene times reveal the existence of three main tectonic periods, separated from each other by intervals of extensional regime or of tectonic relaxation. Each period can be subdivided in turn into various tectonic events (Figure 19).

The "Virú" period (Kimmeridgian-Berriasian) begins with the Kimmeridgian (?) Virú 1 event, marked by the resumption of clastic deposits in southern Peru. Although it is still poorly understood, it can be interpreted as a distal response of the Argentina-Chilean "Araucan" phase. The Tithonian Virú 2 phase is expressed by the creation of a deep turbiditic trough in northern Peru, by the opening of a back-arc basin in the coast of central Peru, and by the emergence of most of southern (and eastern?) Peru. It is interpreted as the consequence of both the accretion of allochthonous terranes in northwestern Peru and Ecuador, and an important extensional phase in Central and Northern Peru. The Berriasian Virú 3 tectonic event is a major paleogeographic change, mostly expressed by a regional unconformity beneath the Valanginian sandstones. It is related to the rifting of the northern South Atlantic ocean, and to ongoing extension at the margin edge.

The "Mochica" period (Late Aptian-Early Middle Cenomanian) starts with scattered precursory volcanic and tectonic extensional manifestations of Late Aptian-earliest Albian age (Mochica 1 phase). It continues during Early and Middle Albian times, with alternating compressional and extensional events within the arc or back-arc volcanic rocks (Mochica 2 phase). These are thought to express either the opening of a marginal basin, or the wrenching and pulling apart of a volcanic arc. The Mochica period ends with the accretion, folding and emergence of these volcanic centres by Late Albian to Early Middle Cenomanian times (Mochica 3 phase).

The "Peruvian" period (Coniacian-Campanian) begins at the Turonian-Coniacian boundary with a major paleogeographic change, probably due to the uplift of the coastal area, causing both an invasion of fine-grained detrital material over the entire margin, and a sharp decrease of subsidence in the Western Trough (Peruvian 1 phase). The Late Coniacian to Middle Campanian times are marked by the start of northeastward overthrusts in southern Peru (Peruvian 2 phase) and by the progressive emergence of the Peruvian margin. They are interpreted as the structural inversion of the southwestern edge of the Western Trough. The Peruvian period culminates with the Late Campanian Peruvian 3 phase, expressed by the development of a foreland basin belt located on the eastern side of the incipient Marañón and Mañazo thrusts. The latter are regarded as the expression of a structural inversion of the northeast border of the Western Trough.

The "Incaic" 1 phase (Paleocene-Eocene boundary) then marks the beginning of the Andean orogeny s.s.

Geodynamic Evolution of the Peruvian Margin

An extensional regime is thought to have been dominant at the trench during latest Jurassic and Early Cretaceous times, and to have induced the magmatic quiescence of the volcanic arc and an oceanward retreat of the oceanic slab.

A compressional regime is then believed to have begun at the trench in the Late Aptian, as the South American plate began to shift westward, and the subducted oceanic lithosphere became younger and arrived faster at the trench. The "Mochica period" is interpreted as the time-span necessary for the trench to migrate up to the border of the continental margin, leading to the consumption of the supposedly aborted marginal basin or to the deformation of the volcanic arc, up to their accretion on the continental margin.

The subsequent "Peruvian period" resulted from the northeastward propagation of the compressive strain within the South American Plate, which caused the structural inversion of the major pre-existing inherited structures, that is: the Cenomanian suture (Peruvian 1) and the western and eastern boundaries of the Western Trough (Peruvian 2 and 3, respectively).

Most of the tectonic events correlate with plutonic gaps, caused by compressive closure of the crustal features channelling the magma. The main tectonic, extensional or compressive phases coincide with quickening or slackening periods in the convergence between the oceanic plate and South America. Though little is yet known about them, dextral wrenching movements probably played an important part in the tectonic evolution of the Peruvian margin.

In more general terms, the determining factors in the tectonic evolution of a continental active margin seem to be: (1) the age of the subducted slab and the convergence rate at the trench, which determine the general strain regime of the trench-margin system; (2) pre-existent extensional or even compressional structures of the continental margin, which determine the tectonic expression and location of the propagating strain; (3) variations (quickening or slowing down) of the convergence rate, which bring about the major tectonic phases.

According to this model, the answers to the problems outlined at the beginning of this paper are:

During the Early Cretaceous, no chain formed along the active Peruvian continental margin, because subduction was low and involved an old oceanic slab. This induced a steep-dipping, "Mariana-type" subduction regime (Uyeda and Kanamori, 1979), characterized either by a magmatic quiescence or by the development of extensional back-arc basins.

After Late Aptian times, and in spite of a compressional tectonic regime due to an acceleration of the convergence rate and rejuvenation of the oceanic lithosphere at the trench -which brought about a possibly low-dipping, "Chilean-type" subduction (Uyeda and Kanamori, 1979)- neither was any chain formed during Middle Cretaceous times, because the shortening was first accommodated by deformation of the marginal basin or the volcanic arc, before the continental margin itself became involved in compressive deformation processes.

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Kimmeridgian? to Paleocene Tectonic Evolution of Bolivia

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Abstract

The Puca Group (Kimmeridgian?-Paleocene) of Bolivia recorded the external (distal) tectonic evolution of the Andean back-arc basin in these latitudes. Bolivia had been part of stable cratonic South America until Late Jurassic time, when it was captured by the Andean system during a large-scale extensional "Araucan"-age tectonic event. This episode seems to be related to the onset of large-scale extensional and transtensional conditions in northern Chile and coastal Peru. In Bolivia, it led to initiation of the tectonically-controlled, highly fragmented Potosí basin filled with unfossiliferous continental siliciclastic deposits (mostly red beds), with relation to the reactivation of the major transversal Khenayani-Turuchipa paleostructural corridor. Extension was locally accompanied by basic volcanism, and created a tilted-block structure, with half-grabens showing topographic downwarps and uplifts upon which younger fine-grained strata onlapped. The oldest and most important extensional episode took place during deposition of the lowermost part of the Puca Group (Condo conglomerates). A younger minor extensional episode developed locally, possibly in Late Neocomian and/or Aptian time. Albian? time saw a large-scale onlap of brown to violet-red mudstones over the previous deposits and, locally, on the Paleozoic basement, indicating a relative change in the tectonic setting, marked by a slow and gentle widening of the sedimentation area without any small-scale extensional manifestations.

Shallow-marine carbonates were deposited during the Cenomanian-Turonian interval, in an area of lesser extension than the Kimmeridgian?-Albian? basin. In this unit, thickness variations are very gentle, sedimentation rates seem very low and no direct indication of synsedimentary tectonics is known. It is thus assumed that this transgression was mainly of global-eustatic origin.

The Senonian-Paleocene sequence consists of a thick pile of mainly mudrocks beds. It was deposited in the external part of the wide, underfilled foreland basin of the paleo-Andes, which at that time were of small size and had produced only a minor flexure of the South American lithosphere. The base of the sequence records a noteworthy exten-