Tectonics and uplift in Central Andes (Peru, Bolivia and Northern Chile) from Eocene to present

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Abstract : *The analysis of sedimentary and volcanic records, exposed in southern Peru, Bolivia, and northern Chile, allow us to establish the chronological evolution of Central Andes from upper Eocene to Present. This analysis is based on field observations and a re-evaluation of the available geological data. It gives evidence for six discrete compressional tectonic pulses that are dated : upper Eocene (ca 42 Ma), upper Oligocene (ca 26-28 Ma), lower Miocene (ca 15-17 Ma), middle Miocene (ca 10 Ma), upper Miocene (ca 7 Ma) and early Quaternary (ca 2 Ma), respectively. The magnitude of shortening and geographical extent of these compressional phases are highly variable. In particular, the lower and middle Miocene compressional pulses could correspond to deformational climaxes chiefly characterized by compressional tectonics. Generally these compressional pulses appear to be coeval with periods of high convergence rate. Moreover, available structural data on these phases suggest that their directions of shortening were roughly parallel to the orientation of convergence. Between these compressional pulses, basin infillings take place ; they are highly variable in thickness and composition and these differences are in agreement with the different mechanics that may be put forward to explain the formations of Andean basin. Consequently they are indicative of the stress regimes that prevail between the compressional pulses. This stress regime should be mainly tensional in the Altiplano, Western Cordillera and Fore-Arc basins. On the contrary, it is essentially compressional in the Subandean Lowlands. Magmatic activity has occurred in the High Andes since at least upper Oligocene time (ca 25 Ma). The magnitude of this magmatic activity appears to be related to the convergence rate. Magmatism was maximum between 25 and 6 Ma, i.e., contemporaneously with the period that is characterized by a higher rate of convergence than the present-day period. Observations performed along the Pacific Lowlands, on Neogene morphological surfaces, show clearly that the high cordilleran topography formed between roughly 26 and 6 Ma, i.e., during the Miocene period of high convergence rate. This Andean uplift has been discontinuous and roughly coeval with the compressional pulses.*

Key words : Tectonics - Uplift - Timing - Cenozoic - Central Andes - Peru - Bolivia - Chile.

Résumé : Tectonique et soulèvement dans les Andes Centrales (Pérou, Bolivie et Nord Chili) depuis l'Éocène jusqu'à l'actuel. *L'analyse des séries sédimentaires et volcaniques, qui affleurent dans le Pérou sud, la Bolivie et le Chili nord, permet d'établir l'évolution chronologique des Andes Centrales de l'Éocène à l'actuel. Cette analyse est basée sur des observations de terrains et une ré-évaluation des données géologiques disponibles. Elle met en évidence six phases tectoniques compressives, datées respectivement de l'Éocène supérieur (≈ 42 Ma), de l'Oligocène supérieur (≈ 26-28 Ma), du Miocène inférieur (≈ 15-17 Ma), du Miocène moyen (≈ 10 Ma), du Miocène supérieur (≈ 7 Ma) et du Quaternaire ancien (≈ 2 Ma). Le raccourcissement et la répartition géographique de ces phases sont très variables. En*

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particulier. les phases compressives du Miocène inférieur et moyen pourraient correspondre à des pics de déformations dans une période de tectonique essentiellement compressive. En général. ces phases de tectoniques compressives apparaissent contemporaines des périodes à taux de convergence élevés. D'ailleurs, les rares données structurales disponibles suggèrent que les directions de raccourcissement sont approximativement parallèles à la direction de la convergence entre les plaques Nazca et Amérique du Sud. Entre ces phases se produit le remplissage des bassins sédimentaires andins. Ces remplissages sont très variables en épaisseur et en composition et ces différences sont en accord avec les différents mécanismes qui peuvent être invoqués pour expliquer la formation des bassins andins. En conséquence. ils sont indicatifs des régimes de contrainte qui prévalent entre les phases compressives. Ce régime de contrainte est plutôt en extension dans l'Altiplano, dans la Cordillère Occidentale et dans les bassins de fore-arc. En revanche, il est essentiellement compressif dans les collines sub-andines. L'activité magmatique est localisée dans les Hautes-Andes au moins depuis l'Oligocène (≈ 25 Ma). L'importance de cette activité magmatique paraît être liée à l'importance du taux de la convergence. Le magmatisme a été maximal entre 25 et 6 Ma. c'est-à-dire contemporain de la période qui est caractérisée par un taux de convergence plus élevé que l'actuel. Les observations réalisées le long de la partie émergée du fore-arc, sur des surfaces morphologiques néogènes, montrent clairement que la haute topographie cordilléraine s'est formée approximativement entre 26 et 6 Ma, c'est-à-dire durant la période miocène de fort taux de convergence. Ce soulèvement andin a été discontinu et à peu près contemporain des phases compressives.

Mots-clés : Tectonique - Soulèvement - Chronologie - Cénozoïque - Andes-Centrales - Pérou - Bolivie - Chili

Resumen : **Tectonica y levantamiento en los Andes Centrales (Peru, Bolivia y Norte de Chile) desde el Eoceno.** *El análisis de las series sedimentarias y volcánicas en el Sur de Peru, Oeste de Bolivia y Norte de Chile nos permite de establecer la cronologiá de la evolución geodinámica de los Andes Centrales desde el Eoceno superior. El estudio se realizó mediante trabajos de campo y tambien compilaciones y evaluaciones de los datos publicados. Seis eventos tectónicos compresivos pueden distinguirse . Eoceno superior (≈42 Ma). Oligoceno superior (26-28 Ma). Mioceno inferior (15-17 Ma). Mioceno medio (≈ 10 Ma), Miocene superior (≈7 Ma), y Cuaternario antiguo (≈2 Ma). La intensidad y el area abarcado por cada uno de estos eventos compresivos es muy variable. Generalmente estas fases tectonicas compresivas se producen durante los periodos de alta velocidad de las placas convergentes ; ademas los escasos datos estructurales parecen indicar que las direciones de acortamiento estan paralelas con la direción de convergencia de las placas de Nazca y America del Sur. El relleno de las cuencas sedimentarias andinas occure entre estas fases. Los rellenos varian tanto en potencia como en naturaleza. y estas diferencias reflejan los ambiantes tectónicos que regian entre los fases compresivas. Se nota que los esfuerzos son esencialmente extensionales en el Altiplano, en la Cordillera Occidental y en las cuencas del ante-arco. En cambio. son mayormente compresivos en el Sub-andino. La actividad magmática esta localisada en los Altos Andes, por lo menos desde el Oligoceno ; el magmatismo ha sido más activo entre 25 y 6 Ma. y su intensidad parece relacionada con la velocidad de las placas en convergencia. Las observaciones, a lo largo de las partes emergidas del ante-arco, de las paleotopografias neogenas indican que la alta superficie cordillerana se hizo entre 26 y 6 Ma. es decir durante el periodo mioceno de alta velocidad de convergencia. El levantamiento andino se ha producido de manera discontinuo, con breves periodos de levantamiento mas o menos sincronos de las fases tectonicas compressivas.*

Palabras claves : Tectonica - Levantamiento - Cronograma - Cenozoico - Andes Centrales - Peru - Bolivia - Chile norte.

INTRODUCTION

High plateaus, such as Tibet or Central Andes, that are related to convergent setting are clearly characterized by a tensional deviatoric state of stress (ARMIJO *et al.*, 1986 ; SÉBRIER *et al.*, 1985 ; LAVENU, 1986 ; MERCIER *et al.*, 1987). One of the major problems is thus to understand how their high topography has been formed. The aim of this paper is thus to report data on the formation of the Andean Cordillera, in southern Peru, western Bolivia and northern Chile, i.e., between about 14° and 20°S. Data presented here proceed from field observations and from a re-evaluation of the available geological information. Our studies indicate clearly that the Andean style of deformation has been variable, the best evidence of stress variation being the occurrence of several angular unconformities of regional extent which show that compressional structures have been formed discontinuously. Assuming that angular unconformities included within overlapping time-spans are contemporaneous, six discrete compressional pulses can be distinguished since 40-45 Ma B.P. In addition, morphological observations show that these tectonic pulses appear roughly coeval with discontinuous phases of uplift which are chiefly responsible for the formation of the Cordilleran topography between 26 and 7 Ma.

CHRONOLOGICAL AND SEDIMENTOLOGICAL EVOLUTION

In southern Peru, Bolivia and northern Chile (fig. 1), present-day topography from the Peru-Chile trench to the Brazilian shield defines three parallel major regions that characterize the Central Andes : (1) the Andean Fore-Arc, (2) the High Andes, and (3) the Andean Foreland. Region 1 can be subdivided into two morphostructural zones (fig. 2) : the submerged Andean slope and the emerged *Pacific Lowlands* that are separated by the basement uplift of the Coastal Cordillera. Lying eastward of the trench, between depth of 7 000 and 2 000 m, the lower and middle slope is almost exempt of sediment and if an accretionary prism is present it is very small and restricted to the lowermost slope (von HUENE *et al.*, 1985). The upper slope, shallower than a depth of 2 000 m, corresponds to the outer fore-arc basins (MACHARÉ *et al.*, 1986). We have analyzed only the emerged eastern edge of these slope basins which crop out along the *Pacific Coast*. Region 2 constitutes the high Andean plateau whose mean elevation is over 4 km ; it is subdivided into three morphostructural units (fig. 2) : the *Western Cordillera*, the *Altiplano*, and the *Eastern Cordillera*. Region 3 is composed of the Subandean zone and of the Amazonian Foreland plain (fig. 2). Due to the scarcity of the data in region 3, we have grouped them as the *Subandean Lowlands*. All these six morphostructural units formed during the Meso-Cenozoic evolution of the Central Andes. Their main characteristics are summarized below.

The Pacific Coast

The Pacific Coast corresponds to the uplifted eastern edge of the Cenozoic marine upper slope basins which are limited to the East by the Coastal Cordillera. This latter constitutes a 1 000 to 1 500 m high scarp which overlooks the Pacific Ocean, indicating that a major fault zone lies oceanward from the coastline (BRUGGEN, 1950 ; PASKOFF, 1978 ; SÉBRIER *et al.*, 1979 ; MACHARÉ *et al.*, 1986). In contrast, its continental side toward the Pacific Piemont is generally fairly flat, with its top being cut by flat topography that corresponds to a Tertiary morphological surface : the Coastal Tarapaca Pediplain in northern Chile (MORTIMER et SARIC, 1972) and the Coastal Cordillera Top Surface in southern Peru (SÉBRIER *et al.*, 1979). The substratum of

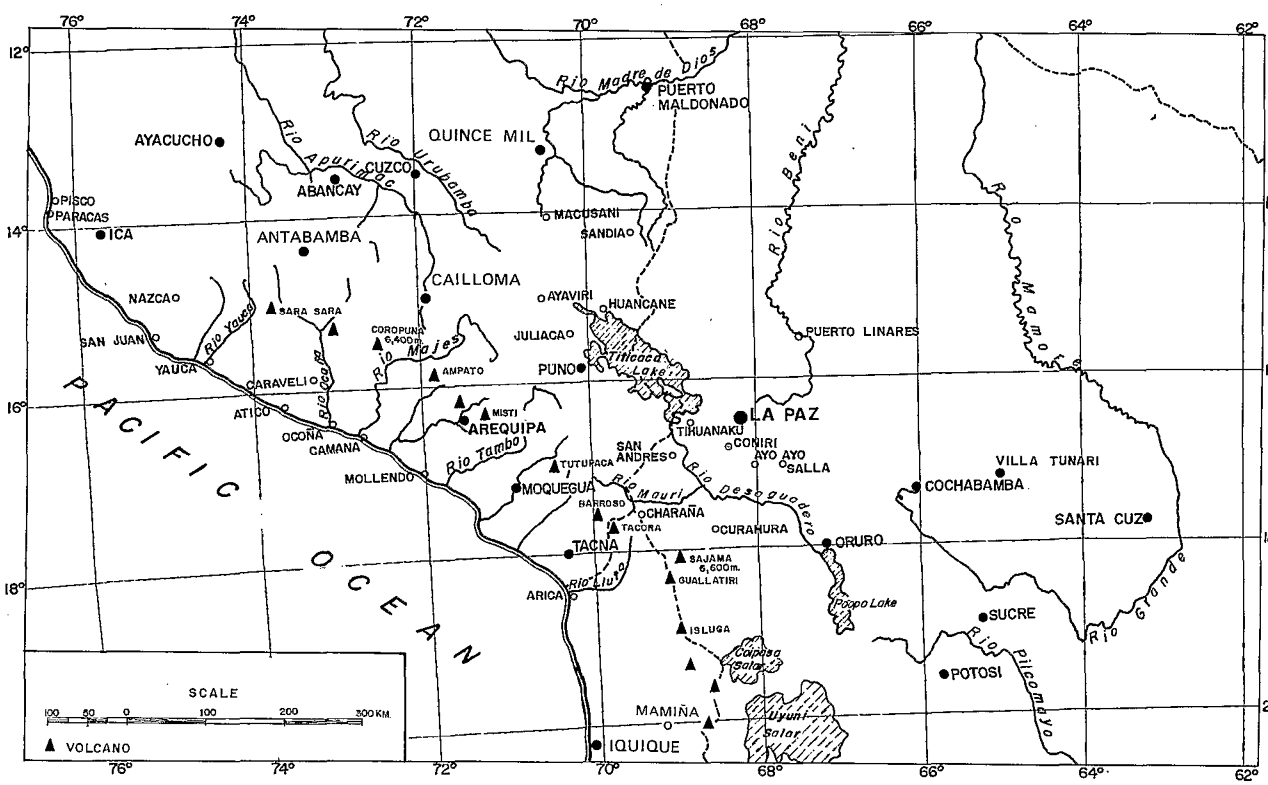

Fig. 1. — Map showing main hydrographic features, active volcanoes (black triangles) and localities names used in the text. Dolted lines indicate boundaries between Peru, Chile, Bolivia and Brazil

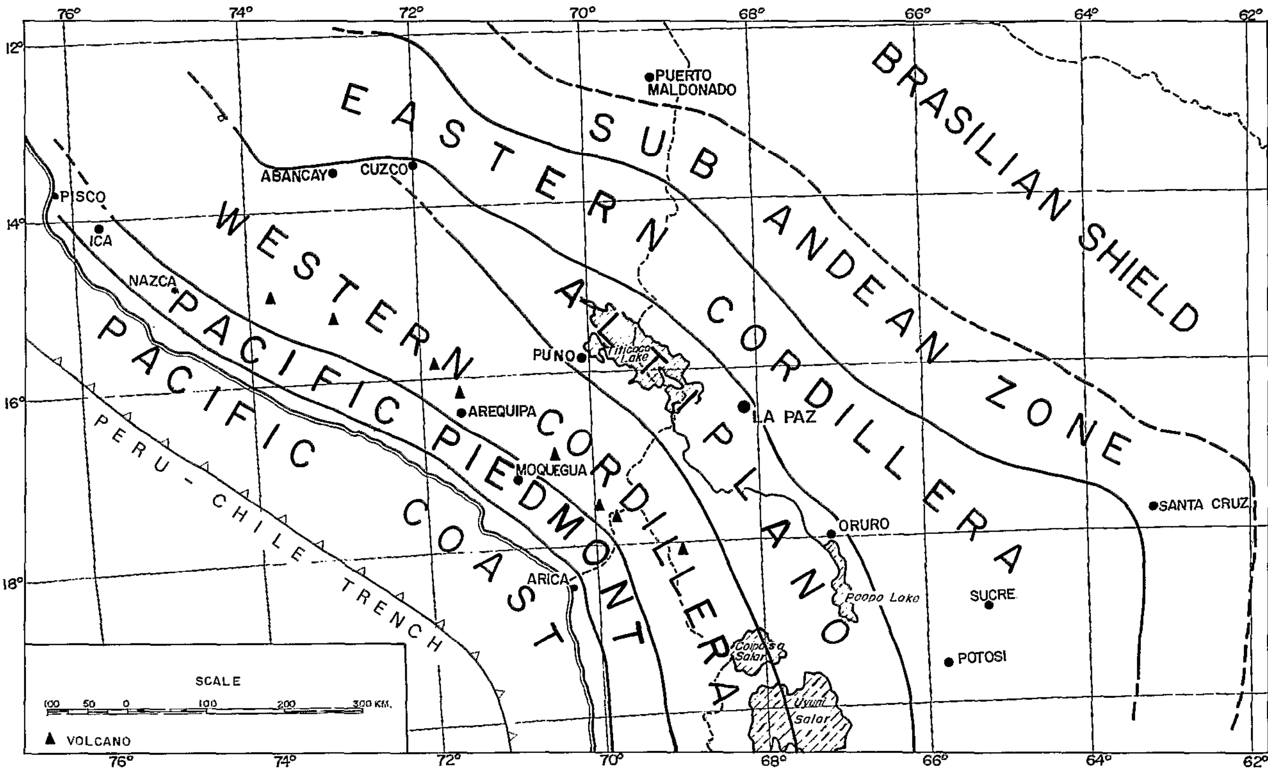

Fig 2 — Morpho-structural zonation sketch. Line with attached open triangles indicates the axis of the Peru-Chile trench

Cenozoic deposits is made of Precambrian and Paleozoic rocks locally overlain by Mesozoic marine volcanic formations.

Scattered deposits of at least five major Cenozoic marine cycles crop out along the Pacific Coast ; they have yielded the following ages : upper Eocene, upper Oligocene-lower Miocene, upper Miocene, Pliocene, and Pleistocene-Holocene (fig. 3 and 4). These Cenozoic marine cycles are separated by unconformities, locally angular, and have cut several marine terraces that give a notched aspect to the coastal scarp. At several localities, these terraces are covered with deposits exhibiting retrogradational depositional structures, which clearly indicate that the terraces have been cut by marine transgressions onto a subsident margin. Generally, the huge coastal scarp has prevented Cenozoic transgressions to progress inland, and as a consequence nearly all the remaining Andean domain has been continental throughout the Cenozoic. Each Cenozoic marine cycle is characterized by a vertical evolution that from bottom to top show decreasing clast sizes and bed thickness. Breccias, conglomerates, coarse sandstones are seen toward the bottom while lutites, shales, clayish sands are exposed toward the top. Much evidence of basinal instabilities are also observed (submarine sliding, syn-sedimentary faults..). All these observations indicate that Cenozoic marine beds were thus deposited onto mobile continental shelf or upper slope basins that were episodically uplifted and slightly deformed by compressional tectonics.

In the *northernmost part of South Peru*, the Ica region (14°S) exhibits the most comprehensive marine record. In fact this area shows affinities with the subsiding marine fore-arc of central Peru (MACHARÉ *et al.*, 1986). From bottom to top the following marine formation are observed (fig. 4).

The *Paracas Formation* (PETERSEN, 1954 ; NEWELL, 1956 ; RÜEGG, 1956) consists some 600 m of yellow-ochre sandstones, shales and siltstones intercalated with limestones, and reworked tuffs. These beds have yielded upper Eocene fossils, with the reported Oligocene ones belonging to the unconformable Caballas formation (MACHARÉ *et al.*, 1986).

The *Caballas formation* (MACHARÉ *et al.*, 1986) consists of some 300 m of shales and sandstones. An upper Oligocene-lower Miocene age is supported by paleontological determinations made on these deposits.

The *Lower Pisco formation* (de MUIZON and DEVRIES, 1985 ; de MUIZON and BELLON, 1986) consists of about 500 m of upper Miocene beds that overlie uncomformably the Caballas formation (MACHARÉ *et al.*, 1986). It is made of yellowish sandstones, lutites, diatomites and limestones (PETERSEN, 1954 ; RUEGG, 1956).

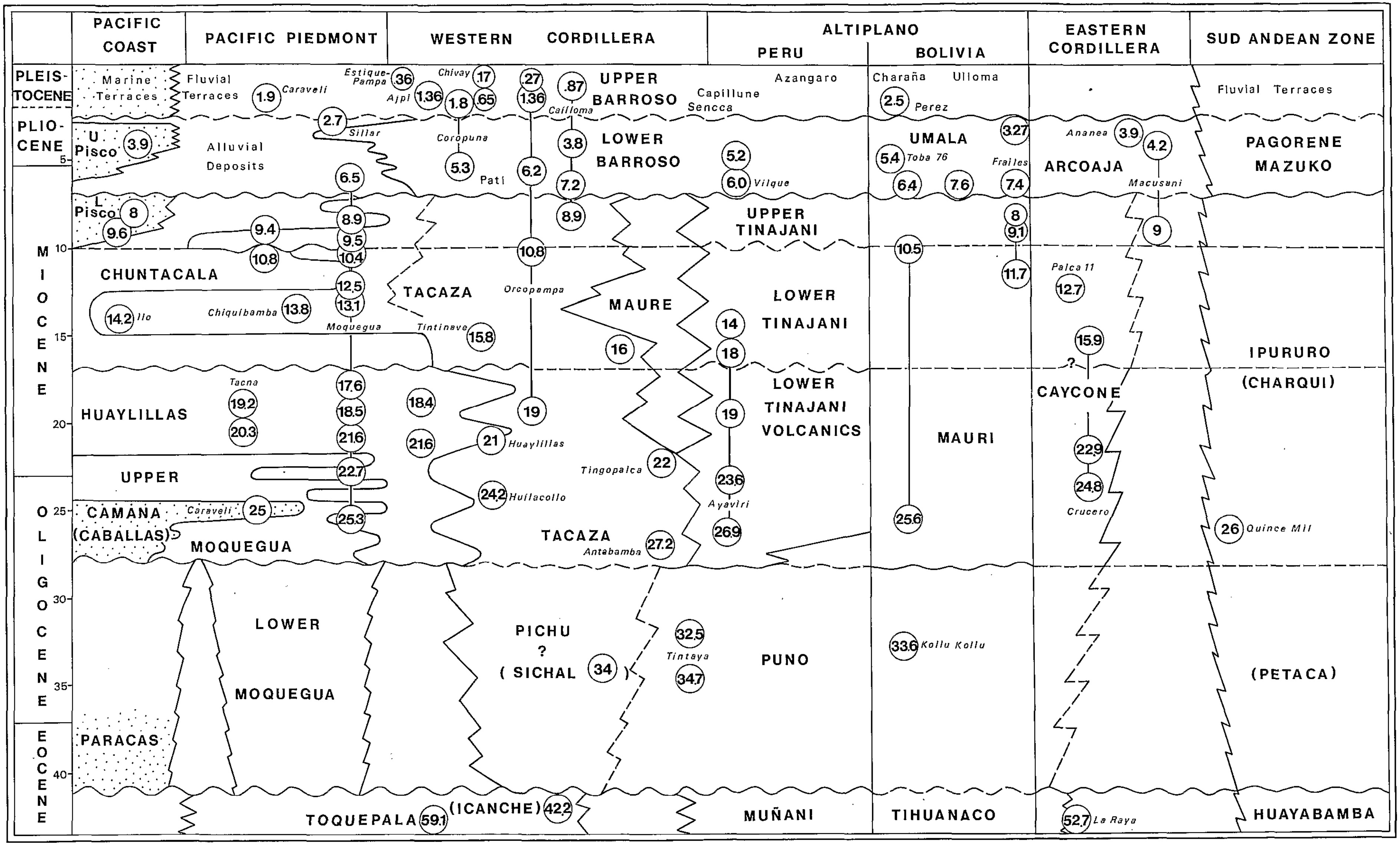

Fig. 3. — Chronological table showing the correlations of the Cenozoic formations and the timing of the compressional deformations. names in block letters (i.e : Puno) represent regional formation. Italic prints are used for local formations or facies (i.e : Nazca). Radiometric ages are located inside circles, they are in million years ; more precisions are given in the text. Marine formations are represented by stippled areas. Undulating lines represent the compressional tectonic phases, where they are dotted the kind of geometric relation between the formations is not known

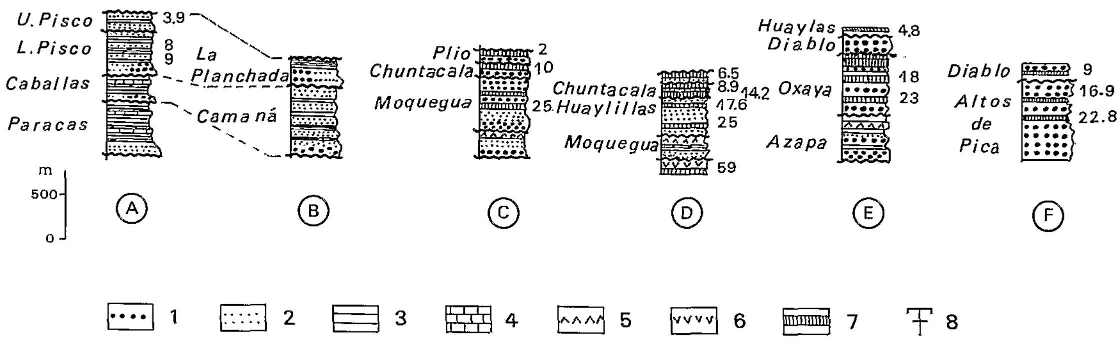

Fig. 4. — Lithological columns of the Pacific Coast and Lowlands sections. A : Pisco (14°S, 76°W) ; B : Camana (16°30'S, 73°W) ; C : Caraveli (16°S, 73°30'W) ; D : Moquegua (17°30'S, 71°W) ; E : Arica (18°30'S, 70°W) ; F : Mamiña (20°S, 69°30'). 1 : Conglomerates ; 2 : Sandstones ; 3 : Pelitic rocks ; 4 : Carbonates ; 5 : Gypsum ; 6 : Lavas ; 7 : Tuffs ; 8 : Fossilbearing level. Numbers : Radiometric dates in Million Years

The *Upper Pisco formation* (de MUIZON et and DEVRIES, 1985) overlie unconformably the Lower Pisco formation. It consists of some 150 m of sandstones and siltstones intercalated with diatomites, tuffs and evaporites. Radiometric and paleontological determinations give a Pliocene age to this formation (de MUIZON, 1979 ; de MUIZON and BELLON, 1980).

Pleistocene marine terraces crop out only along the coastal scarp. Their great elevation that reaches approximately 600-700 m is interpreted as a consequence of the aseismic Nazca ridge subduction beneath this part of the fore-arc (MACHARÉ *et al.*, 1986.

In *central southern Peru*, around Camana (16°30'S), the following formations can be observed (fig. 4) :

The *Camana formation* (RIVERA, 1950 ; RÜEGG, 1952 ; PECHO and MORALES, 1969) is composed of 600-800 m of yellowish lutites, sandstones, and limestones that have yielded upper Oligocene to lower Miocene fossils (RÜEGG, 1952 ; DROOGER, 1953 ; PARDO *in* PECHO and MORALES, 1969). It is thus a lateral-equivalent of the Caballas formation. This transgression went over the Coastal Cordillera, cutting its top surface (SÉBRIER *et al.*, 1979), and invaded the Pacific Piedmont in the vicinity of Caraveli (SÉBRIER *et al.*, 1982 ; HUAMAN, 1985).

The *La Planchada formation* (LAHARIE, 1975 ; BEAUDET *et al.*, 1976) consists of sandstones, sands, lutites, and conglomerates of Pliocene age. It overlies unconformably the Camana formation, being inset within it. Its outcrops are seen up to an elevation of some 250 m.

In *Northernmost Chile*, between Arica (18°30'S) and Antofagasta (23°30'S), Miocene and Pliocene marine beds are known along the Coast. The largest outcrops are exposed to the North of Antofagasta where the Pleistocene Mejillones Formation overlies unconformably the Miocene-Pliocene La Portada Formation (FERRARIS and DI BIASE, 1978).

The Pacific Lowlands

The Pacific Lowlands is a 70 km wide unit that constitutes a series of elongated basins known as the Pacific Piemont (fig. 2) in Peru and the Longitudinal Depression in Chile. Its flat topography, i.e., South Peruvian « Pampas » or Chilean « Pampa del Tamarugal », is gently inclined seaward and incised by deep canyons. Its substratum is similar to that of the Coastal Cordillera, but Mesozoic marine and early Tertiary continental volcanic rocks and their plutonic counterparts are much more common.

The Pacific Lowland basins are slightly asymetric. As mentioned above (see § « The Pacific Coast ») their contact with the Coastal Cordillera in general is not faulted, excepted in the Chilean Antofagasta region (23°S) where the east-facing Atacama fault is exposed (OKADA, 1971). In contrast, the eastern edge of these Pacific Lowland basins is generally faulted by a west-facing, often east-dipping major fault zone that separates them from the High Andes, the upthrown block. The Pacific Lowland basins are thought to have initiated approximately during Oligocene time, because their deposits are overlying unconformably volcanic beds that are related to a Paleocene to Eocene (only known in northern Chile) magmatic arc (LAUGHLIN *et al.*, 1968 ; QUIRT *et al.*, 1971 ; SILLITOE, 1981 ; COIRA *et al.*, 1982 ; VATIN-PÉRIGNON *et al.*, 1982). These basins are filled with unfossiliferous continental clastic deposits, which are interbedded with numerous ignimbritic tuffs that allow generally these deposits to be dated. The sedimentary evolution can be divided into two major periods : (1) from Oligocene to lower-middle Miocene, basins are characterized by aggradational processes while, (2) from upper Miocene to Present, degradation prevails. In detail, major aggradation ceased during lower Miocene (ca 17 Ma) in southern Peru (SÉBRIER *et al.*, 1982 ; TOSDAL *et al.*, 1984 ; HUAMAN, 1985), while it ended after 12 Ma and prior to 10 Ma in northern Chile (MORTIMER, 1973). This discrepancy may reflect climatic differences or limted knowledge of the Longitudinal Depression filling.

In the Pacific Lowlands, i.e., in the inner fore-arc basins, the Oligocene to Present evolution can be summarized as a succession of five series (fig. 3 and 4).

(1) The Lower Oligocene series are characterized by clastic red beds intercalated with many evaporitic beds (mainly gypsum). They are known in Peru, as the *Lower Moquegua Formation* (STEINMANN, 1929 ; SÉBRIER *et al.*, 1979 ; MAROCCO *et al.*, 1986), and in Chile as the Azapa (SALAS *et al.*, 1966), Sichal (MAKSAEV, 1979) and San Pedro-Tambores Formations (LAHSEN, 1982). Only two of these formations, located in the Precordillera nearby the boundary between the Western Cordillera and the Longitudinal Depression (22°S, 69°W), have in fact yielded K/Ar radiometric ages : the Sichal, 34.7±1 Ma (MAKSAEV, 1978) and the San Pedro, 28±6 Ma (TRAVISANY, 1978).

(2) The Upper Oligocene to lower Miocene series correspond to Piemont deposits of gravels conglomerates and sandstones intercalated with gypsum and ignimbritic tuffs. These beds unconformably overlie series 1. They are known, in Peru as the *Upper Moquegua Formation* (STEINMANN, 1929 ; SÉBRIER *et al.*, 1982 ; TOSDAL *et al.*, 1984) and the *Huaylillas Formation* (WILSON and GARCIA, 1962 ; SÉBRIER *et al.*, 1979 ; TOSDAL *et al.*, 1981), and in Chile as the Oxaya Formation (SALAS *et al.*, 1966) ; or the Tamarugal gravels (GALLI and DINGMAN, 1962). In fact the Upper Moquegua Formation corresponds mainly to clastic facies while the Huaylillas Formation is mainly made of ignimbritic tuffs that have yielded ages ranging between 25 and 17 Ma (MORTIMER *et al.*, 1974 ; BELLON and LEFEVRE, 1976 ; BAKER and FRANCIS, 1978 ; NOBLE *et al.*, 1979 ; TOSDAL *et al.*, 1981 ; COIRA *et al.*, 1982 ; LAHSEN, 1982 ; VATIN-PÉRIGNON *et al.*, 1982 ; SÉBRIER *et al.*, 1983). In southern Peru around Caraveli (16°S), a marine ingression is interbedded in the Upper Moquegua Formation (SÉBRIER *et al.*, 1979 ; HUAMAN, 1985), it is dated on plagioclase at 25.5±1 Ma and on biotite at 24.5±0.8 (NOBLE *et al.*, 1985) ; these are the only Cenozoic marine beds known in the whole inner fore-arc basins of southern Peru and northern Chile.

(3) The middle to upper Miocene series is characterized by gravel deposits intercalated with ignimbitic tuffs and andesites dated between 7 and 15 Ma (MORTIMER *et al.*, 1974 ; TOSDAL *et al.*, 1981 ; LAHSEN, 1982 ; HUAMAN, 1985). Miocene series 3 rest unconformably on upper Oligocene-lower Miocene series 2. In addition in southern Peru, they partly fill broad valleys that were excavated within series 2. In northern Chile they correspond to a wide erosional surface known as the Tamarugal pediplain (MORTIMER and SARIC, 1975). Series 3 beds are known as the *Chuntacala Formation* in Peru (MANRIQUE and PLAZOLLES, 1974 ; TOSDAL *et al.*, 1981 and 1984 ; SÉBRIER *et al.*, 1982) and the Diablo Formation in northern Chile.

(4) The Pliocene series is characterized by facies similar to those of Miocene series 3. In addition, these Pliocene beds partly fill deep canyons incised within Miocene series 3 during uppermost Miocene time (MORTIMER, 1973 ; LAHARIE, 1975 ; SÉBRIER *et al.*, 1979 and 1982 ; TOSDAL *et al.*, 1981 and 1984).

(5) The Pleistocene series consists of three stepped fluvial terraces that were deposited while rivers were down-cutting present-day valleys within Pliocene series 4 (SÉBRIER *et al.*, 1982).

The Western Cordillera

The Western Cordillera is approximately 150 km wide and forms a high plateau with a mean elevation of 4 500 m. On its top, 5 000- to 6 000 m high calc-alkaline active volcanoes lie ; they correspond to the main magmatic arc. This last one is characterized by the pilling up of Cenozoic volcanic materials. The substratum of Cenozoic volcanics consists mainly of Mesozoic marine clastic rocks that are cropping out in few places : in the bottom of deep canyon valleys or at the top of paleo-relief.

In the Western Cordillera, lithologies and thicknesses are highly variable (fig. 5). However two main volcanic groups, Oligo-Miocene and Plio-Pleistocene, may be distinguished (fig. 3 and 5). The Oligo-Miocene group corresponds, in southern Peru to the *Tacaza* group, dated between 24.2 Ma at Paso Huaylillas (17°45'S) on the Peru-Chile border (SÉBRIER *et al.*, 1983 ; BELLON, written com.), and 8.9 Ma at Cailloma (FORNARI *et al.*, 1983) ; in Bolivia it corresponds to the Mauri, Abaroa and Upper Quehua Formations dated between 26 and 10.5 Ma (EVERNDEN *et al.*, 1966 and 1977 ; KUSSMAUL *et al.*, 1973 ; LAVENU, 1986). The Plio-Pleistocene group corresponds, in southern Peru, to the *Barroso* Group and to various local formations such as the Cerke, Perez and Charaña (LAVENU, 1986). Chronological data on northern Chile, reported by LAHSEN (1982), also agree with a subdivision in two main groups. The *Maure* Formation of southern Peru (MENDIVIL, 1965) is a Miocene lacustrine facies interbedded within the Tacaza group. In fact, several Pliocene lacustrine beds are erroneously mapped as Maure, and we suggest to name them Pati Formation as the Pati beds are conformably overlying lower Barroso andesites dated at 4.4 Ma (BELLON and LEFÈVRE, 1976). Pleistocene lacustrine beds such as the Capillune Formation (MENDIVIL, 1977) are interbedded within the Upper Barroso Formation.

The occurrence of lower Oligocene volcanics is still dubious in the Western Cordillera. This epoch appears to be characterized instead by continental clastic red beds such as the Sichal Formation of northern Chile dated at 34.7 Ma (MAKSAEV, 1978) or the Lower Quehua of southwestern Bolivia (KUSSMAUL *et al.*, 1977). In southern Peru the *Pichu* Formation is older than 16 Ma (SÉBRIER *et al.*, 1983). It could thus be either lower Miocene, i.e., coeval with the lower part of the Tacaza Group (Huilacollo and Tingopalca volcanics) or Oligocene as considered by AUDEBAUD *et al.* (1976).

The Altiplano

The Altiplano (fig. 2) is a high endoreic plain situated at a mean elevation of nearly 4 000 m, i.e. slightly

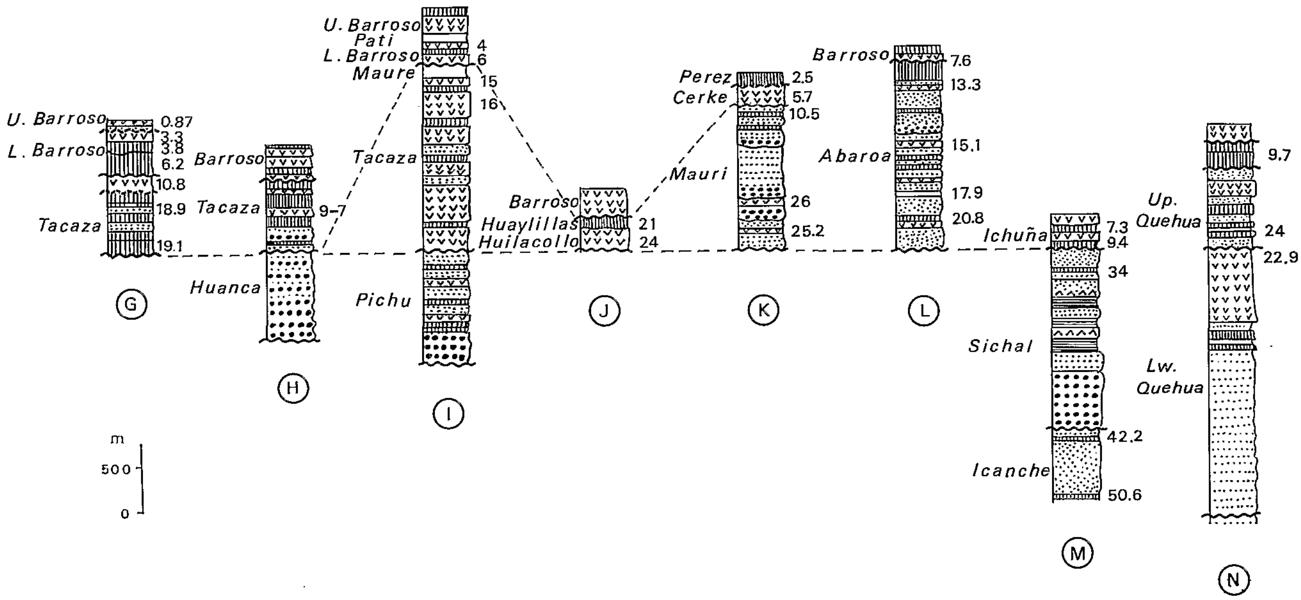

Fig. 5 — Lithological columns of the Western Cordillera sections . G : Orcopampa-Cailloma (15°S, 72°W) . H : Huanca (16°S, 72°W) . I : Ichuña (16°S, 71°W) . J : Huaylillas (17°30'S, 70°W) ; K : Mauri (17°S, 69°30'W) ; L : Abaroa (18°S, 69°W) . M : Upper Rio Loa (21°30'S, 69°W) ; N : Lipez (22°S, 67°W). Symbols as in fig. 4

below the level of the Western and Eastern Cordillera. It is 150 km wide and about 1 500 km long, extending from southeast of Cuzco (14°S) to the Puna of Argentina (27°S). The Altiplano is thus restricted to the central part of Central Andes. During the whole Cenozoic era the Altiplano basin has been strongly subsiding ; the debris resulting from the erosion of the surrounding Cordilleras and from volcanic emissions have accumulated there, lying on a substratum made mainly of lower Paleozoic and Cretaceous rocks.

The Altiplano basin is characterized by very thick continental series of Cenozoic deposits (fig. 6). The most comprehensive sedimentological record is seen in the northern part of the Bolivia Altiplano (Coro-Coro and Umala areas). There, the Cenozoic series could reach 21 500 m (reported in LAVENU, 1986). However, the Cenozoic series has not been deposited continuously ; in fact, five main depositional periods can be distinguised, separated by folding and related unconformities (fig. 3 and 6). The lowermost one is Paleocene-Eocene in age and ends with the Late Eocene Tihuanaku Formation (MARTINEZ, 1980). The following period is lower Oligocene in age, dated near its top at Kollu Kollu at 33.6 Ma (EVERNDEN *et al.*, 1966) Then, the upper Oligocene to upper Miocene period is characterized by a higher rate of deposition (i.e., subsidence rate) : an average of more than 0.5 mm per year that could reach in some members 1 mm per year (LAVENU, 1986). Radiometric dates have been obtained only from its upper part, between 8 and 11.7 Ma (EVERNDEN *et al.*, 1966 and 1977 ; LAVENU, 1986). This upper Oligocene to upper Miocene period is roughly coeval with the Mauri Formation toward the Western Cordillera. The Pliocene period corresponds mainly to lacustrine deposits interbedded with ignimbritic tuffs dated between 7.6 and 3.27 Ma (EVERNDEN *et al.*, 1966 and 1977 ; CLAPPERTON, 1979 ; GRANT *et al.*, 1979 ; LAVENU, 1986). The Pleistocene period is characterized by the deposit of the Paleo-Titicaca and Poopo lacustrine beds, what form a tier of five lacustrine terraces, each separated from the next by a major incision (LAVENU, 1984). Major deposits correspond to the Ulloma Formation, known also as Azangaro Formation on the Peruvian Altiplano. These lacustrine beds are coeval with fluvial terraces and morainic deposits.

Each time that detailed field studies have been performed, the reported thicknesses appeared to be over-estimated (LAVENU, 1986). Nevertheless, the Miocene Coro-Coro series have a thickness of the order of 10 000 m. Therefore, even if the total thickness must be lowered, the Miocene epoch is characterized by a high rate of deposition.

On the Peruvian Altiplano, the Ayaviri area show : (1) the Eocene *Muñani* Formation (AUDEBAUD *et al.*, 1973) ; (2) the Oligocene *Puno* or Ayaviri Formation (CHANOVE *et al.*, 1969 ; AUDEBAUD and VATIN-PÉRIGNON, 1974) ; (3) The *Lower Tinajani Volcanics*, dated between 19 and 27 Ma (BONHOMME *et al.*, 1985) ; (4) The *Lower Tinajani* Formation, dated between 14 and 18 Ma (BONHOMME *et al.*, 1985) ; (4) The *Upper Tinajani* Formation, attributed to upper Miocene (AUDEBAUD *et al.*, 1976) ; and (5) The Barroso Group. In the Puno area, NEWELL (1949) reported a 7 000 m thickness for the Oligocene Puno Formation, it is unconformably covered by the Vilque latites dated between 4.2 and 6 Ma (BELLON and LEFÈVRE, 1976 ; KANEOKA and GUEVARA, 1984 ; FERAUD, written com.), which in turn are covered by the Pleistocene lacustrine beds of the Paleo-Titicaca lake.

The Eastern Cordillera

The Eastern Cordillera (fig. 2) is a 4 000 m high plateau about 150 km wide with some glaciated range summits that are over 6 000 m. During the whole Cenozoic era it was an uplifting area in which some small

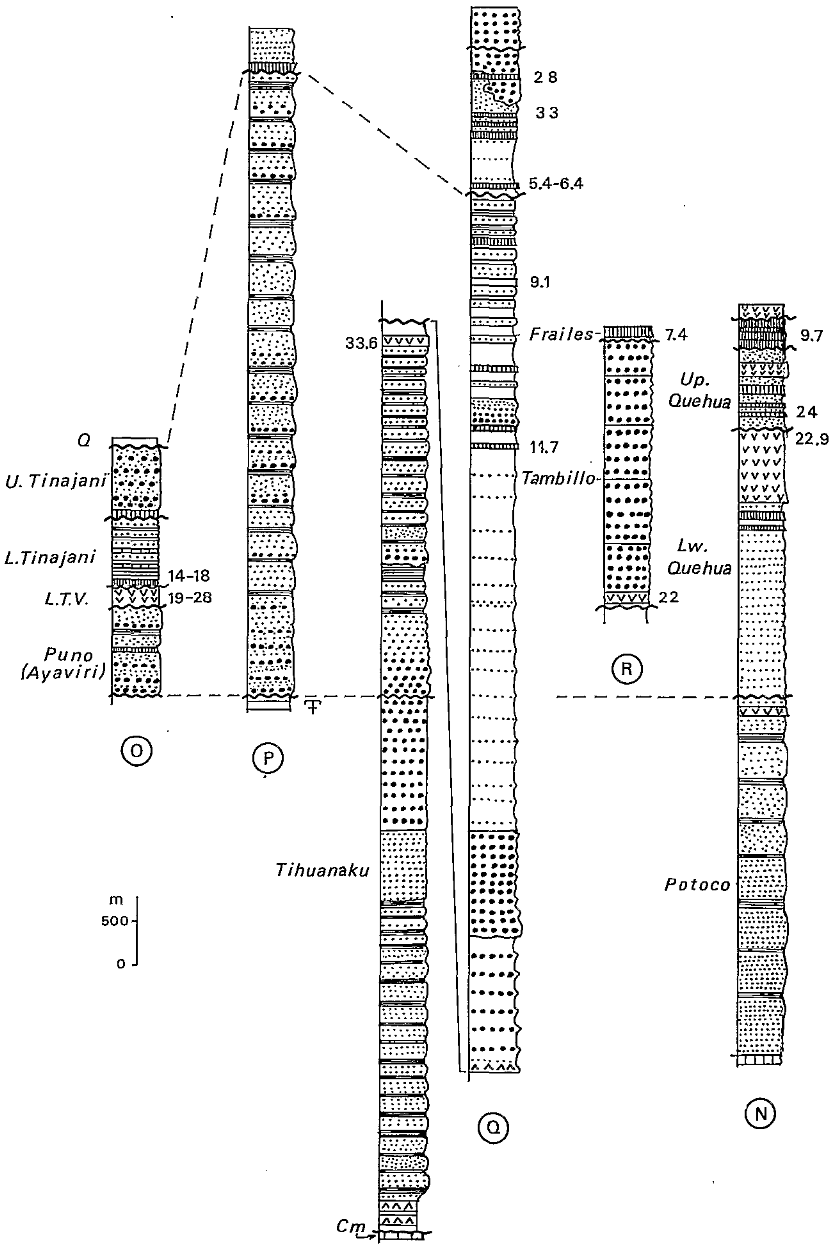

Fig. 6. — Lithological columns of the Altiplano sections ; N : Lipez (22°S, 67°W) ; O : Ayaviri (15°S, 70°30'W) ; P : Puno (16°S, 70°W) ; Q : Coro Coro (17°30'S, 68°30'W) ; R : Tambo Tambillo (19°30'S, 67°30'W). Cm : Middle Cretaceous ; L.T.V. · Lower Tinajani volcanics ; Q : Quaternary. Symbols as in fig. 4

intermontane basins formed. Their substratum is made of Paleozoic and Mesozoic rocks intruded by plutonic material. The Eastern Cordillera corresponds to the locus of the « inner magmatic arc » (CLARK *et al.*, 1983), and since upper Oligocene time, it was characterized by the occurrence of both mantle and crustal derived magmatism.

In southeastern Peru, near Macusani, the Crucero basin is characterized by sedimentary series (fig. 7) that are lithologically similar to those of the Altiplano (LAUBACHER *et al.*, 1987). They consist of : (1) The Oligo-Miocene *Caycone* continental Formation, and (2) the Pliocene *Arcoaja* Formation dated at 3.9 Ma (LAUBACHER *et al.*, 1984a). The whole series is unconformably covered by Pleistocene fluvial terraces and outwash to morainic deposits. The middle part of the Caycone Formation contains sub-alkaline basalts and crustal derived ignimbritic tuffs dated between 15.9 and 24.8 Ma (LAUBACHER *et al.*, in press). In the vicinity of Macusani, the Macusani ignimbritic tuffs, dated between 4.2 and 9 Ma (BARNES *et al.*, 1970 ; NOBLE *et al.*, 1984), fill a paleo-valley oriented toward the Amazonian foothills.

In the Cochabamba basin (fig. 7), continental red beds, attributed to the Paleogene-Miocene epoch, are unconformably overlain by Pliocene lacustrine beds. These ares are folded and covered by Pleistocene fluvial terraces (LAVENU, 1986). In the Potosi area (fig. 7), volcanic and sedimentary bed, dated between 18.8 and 21.9 Ma (EVERNDEN *et al.*, 1966 and 1977 ; GRANT *et al.*, 1979), are cut by the Ag-bearing Cerro Rico stock, dated at about 14 Ma (GRANT *et al.*, 1979). The previous formations are unconformably covered by the Los Frailes ignimbritic tuffs dated at 7.4 Ma (GRANT *et al.*, 1979). In the vicinity of La Paz, the Cordillera Real and Quimsá Cruz exhibit intrusives bodies (fig. 7) dated between 19.2 and 28.4 Ma (McBRIDE *et al.*, 1983).

The Subandean Lowlands

The Subandean Lowlands corresponds to the Amazonian piedmont of the Andes. They formed a subsiding trough in which the debris resulting from the erosion of the Andean Cordillera accumulate (fig. 8). These Subandean Lowlands can be subdivided into two narrow zones : the 50 km wide Subandean zone and the 50 to 100 km wide Amazonian Foreland plain. The Subandean zone is an hilly area, with elevations ranging between 400 and 1 000 m that corresponds to a Cenozoic fold and thrust belt that has been deformed mainly in the late Miocene. The Amazonian foreland plain corresponds to the present-day area of sedimentation and approximately to the easternmost front of the Andean deformations.

Due to unfavourable field conditions, the Subandean geology is still poorly known. From upper Cretaceous to Present it is characterized by five series (fig. 3 and 9). (1) Upper Cretaceous series correspond to sandstones and Maestrichtian marine limestones (DAVILA and PONCE DE LEON, 1971). (2) Paleogene series correspond in southern Peru to the Huayabamba and in Bolivia to the Quendeque and Bororigua Formations (PARDO *et al.*, 1973 ; SANJINES and JIMENEZ, 1976 ; MARTINEZ, 1980). (3) Oligo-Miocene series are formed in southern Peru by the *Ipururo*, and in Bolivia by the Charqui, and lower Oligocene to Miocene Petaca Formations (PARDO *et al.*, 1973 ; SANJINES and JIMENEZ, 1976 ; REYES, 1976). (4) Neogene series correspond, in southern Peru to the *Pagorene* (PARDO *et al.*, 1973) or *Mazuko* Formations (LAUBACHER *et al.*, 1984b) and in Bolivia to the Pliocene Upper Chaco conglomerates (MARTINEZ, 1980). (5) Pleistocene to Present series are composed of fluvial terraces.

TIMING OF COMPRESSIONAL TECTONIC PHASES

In Central Andes, STEINMANN (1929) distinguished three main compressional tectonic phases during the Andean orogenic cycle : the Peruvian, Incaic, and Quechua Phases. These are dated upper Cretaceous (Santonian), upper Eocene, and uppermost Miocene respectively (AUBOUIN *et al.*, 1973 ; AUDEBAUD *et al.*, 1973 ; MÉGARD, 1973, 1978 ; DALMAYRAC *et al.*, 1977, 1980 ; MARTINEZ, 1978 ; MAKSAEV, 1978 ; NOBLE *et al.*, 1979). Nevertheless the above-mentionned authors and additional works (MORTIMER, 1974 ; SOULAS, 1975, 1977 ; KUSSMAUL *et al.*, 1977 ; SÉBRIER *et al.*, 1979, 1980, 1982 ; COIRA *et al.*, 1982 ; LAHSEN *et al.*, 1982 ; MÉGARD,

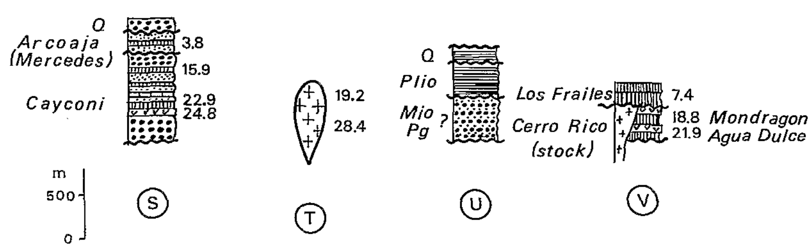

Fig. 7 — Lithological columns of the Eastern Cordillera sections : S : Crucero (14°30'S, 70°W) : T : Cordillera Real-Quimsa Cruz (16°30'S, 68°W) : U Cochabamba (17°30'S, 66°W) . V . Potosi (19°30'S, 66°W). Pg : Paleogene : Mio : Miocene ; Plio : Pliocene ; Q : Quaternary. Symbols as in fig. 4

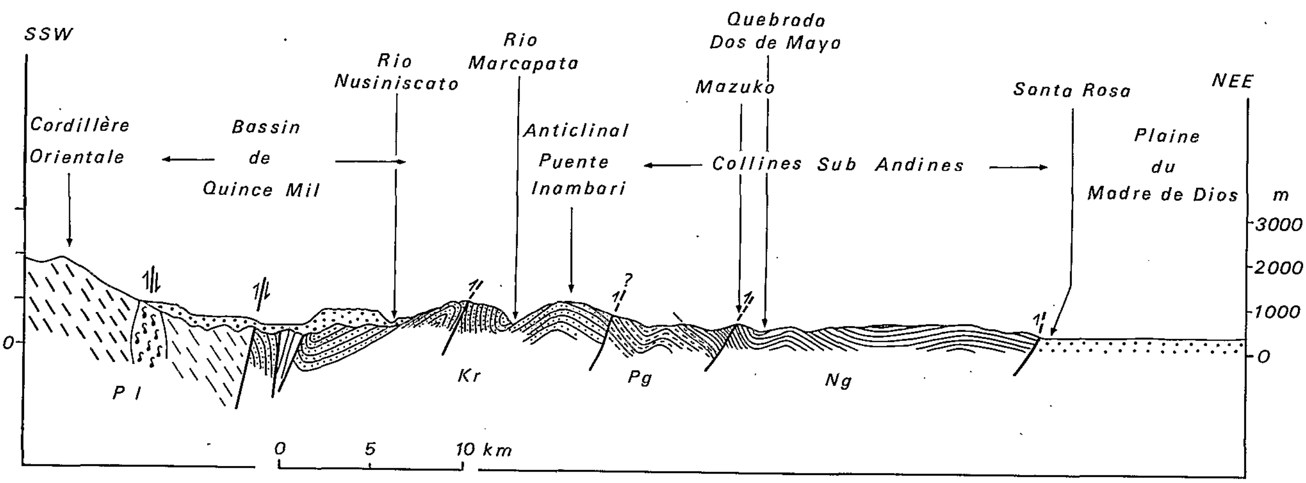

Fig. 8. — Cross section in the southern Peru Subandean Lowlands along the Inambari river. Pl : Lower Paleozoic metamorphic rocks with Upper Oligocene dioritic intrusion ; Kr : Upper Cretaceous sandstones ; Pg : Paleogene red beds ; Ng : Neogene grey beds. Dot pattern : Early Quaternary of the Quince Mil basin and Upper Quaternary of the Madre de Dios river plain

1984 ; MÉGARD *et al.*, 1984) emphasize that the Andean evolution is characterized by more than three tectonic pulses. Even if their spatial distribution and related deformational amplitude are strongly variable, at least 9 discrete pulses can be distinguished with the following ages : Albian (Mochica phase), Santonian (Peruvian phase), uppermost Cretaceous-Paleocene, upper Eocene (Incaic phase), upper Oligocene (Aymara phase), lower Miocene, middle Miocene, upper Miocene (Quechua phase), upper Pliocene-early Quaternary.

The upper Eocene compressional tectonic phase, F1 (ca 42 Ma)

This tectonic phase is one of the major compressional pulse of the Central Andes ; it is observed in most of Andean domain (AUBOUIN *et al.*, 1973 ; AUDEBAUD *et al.*, 1973 ; MÉGARD, 1973, 1984 and 1985 ; DALMAYRAC *et al.*, 1980 ; MARTINEZ, 1980 ; COIRA *et al.*, 1982 ; LAHSEN, 1982 ; MALUMIAN and RAMOS, 1984 ; CAMINOS *et al.*, 1985). In the studied area it is demonstrated by the unconformities seen between (fig. 3) : the Oligocene Puno and Eocene Muñani Formations of the Peruvian Altiplano (CHANOVE *et al.*, 1969) ; and the lower Oligocene Petaca and Paleogene Huayabamba Formations of the Bolivian Sub-Andes (SANJINES and JIMENEZ, 1976). In the Peruvian Pacific Piedmont, the unconformity between the Paleocene Toquepala volcanites and the undated Lower Moquegua Formations may be due to this upper Eocene tectonic pulse. On the Bolivian Altiplano it is not clearly demonstrated, but if it occurred there, its major effect could be the sedimentation of the Coniri conglomerates between the Tihuanaku and Kollu Kollu beds.

In the upper Rio Loa Precordillera of northern Chile (21°30'S) the age of the upper Eocene tectonic pulse is bracketed (MAKSAEV, 1979) between 34 Ma (Sichal Formation) and 42.2 Ma (Icanche Formation). As in central Peru it is prior to 41 Ma (NOBLE *et al.*, 1979) this tectonic pulse should be therefore dated at about 42 Ma.

This upper Eocene compressional pulse has produced the westfacing Putina imbricated thrust zone (LAUBACHER, 1978) that is located along the northern

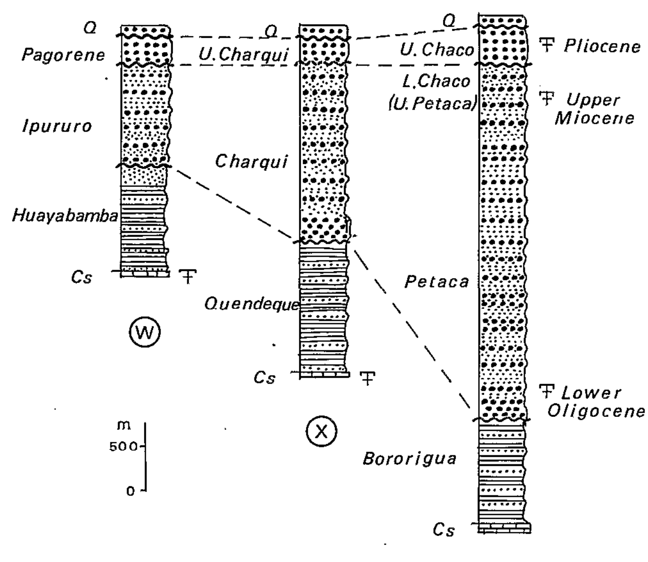

Fig. 9. — Lithological columns of the Subandean Lowlands sections ; W : Madre de Dios (13°S, 70°30'W) ; X : Beni (16°S, 67°W) ; Y : Santa Cruz (18°S, 63°30'W). Cs : Upper Cretaceous ; Q : Quaternary. Symbols as in fig. 4

shore of the Titicaca lake, on the boundary separating the Eastern Cordillera from the Altiplano. We have not performed structural observations of the upper Eocene deformations, nevertheless available data (MÉGARD, 1973 and 1978 ; DALMAYRAC *et al.*, 1977 and 1980 ; MARTINEZ, 1980) suggest that the shortening direction trends roughly NE-SW, i.e., approximately parallel north the upper Eocene convergence of the Farallon and South American plates (PILGER, 1983).

The upper Oligocene compressional tectonic pulse, F2 (ca 26-28 Ma)

The best evidence for an Oligocene compressional phase is found in southwestern Bolivia (fig. 6), where the lower Miocene Upper Quehua Formation dated at 24 Ma overlies with an angular unconformity the Oligocene lower Quehua Formation dated at 22.9 Ma (KUSSMAUL *et al.*, 1975). Although these old ages should be recalculated using new decay constants, they indicate a tectonic pulse located approximately in the upper Oligocene. In the other areas, mapping and regional studies support this conclusion. On the Bolivian Altiplano (fig. 3), MARTINEZ (1978) reports a compressional pulse bracketed between 34 and 26 Ma according to EVERNDEN's (1966) radiometric dating. In northern South Peru, at the boundary between the Western Cordillera and the Altiplano, an angular unconformity is located between an Oligocene magmatic arc, dated at 32.5-34.7 Ma, near Tintaya (NOBLE *et al.*, 1984), and the Tacaza volcanic Formation dated at 27.2±3 Ma near Antabamba (PECHO, 1981). Likewise, on the central Peruvian Altiplano, in the vicinity of Ayaviri (fig. 6), the Lower Tinajani Volcanics, dated between 19 and 27 Ma (BONHOMME *et al.*, 1985), rest unconformably on the Oligocene Puno Formation (AUDEBAUD and VATIN-PERIGNON, 1974) ; in addition, nearby Puno the Tacaza Formation is seen unconformably on the Puno one (NEWELL, 1949). In the Western Cordillera, evidence for an Oligocene phase in unclear because the Pichu Formation remains undated. If its proposed Oligocene age (AUDEBAUD *et al.*, 1976) is confirmed, thus its unconformity with the Tacaza Formation (MAROCCO and DEL PINO, 1966) should be due to an Oligocene pulse. In the Ichuña-Characato area, where the unconformity has been observed, the oldest ages yielded by the Tacaza Formation are about 16 Ma (VATIN-PERIGNON *et al.*, 1982 ; SÉBRIER *et al.*, 1983), they indicate that the Tacaza-Pichu unconformity is at least lower Miocene in age. In the Central Andean Fore-Arc, the Oligocene compressional tectonics is shown by the following unconformities (fig. 4) : (1) in the Ica region, between the upper Oligocene Caballas and upper Eocene Paracas marine Formations (MACHARÉ *et al.*, 1986 and 1988) ; (2) in the Peruvian Pacific Piedmont, between the lower Miocene-upper Huaylillas-Upper Moquegua Formations dated between 17.6 and 25.3 Ma (TOSDAL *et al.*, 1981 ; NOBLE *et al.*, 1985) and the underlying lower Moquegua that is attributed to the Oligocene epoch (AUDEBAUD *et al.*, 1976 ; SÉBRIER *et al.*, 1979 and 1982) ; (3) in the northern Chilean Longitudinal depression, between the lower Miocene Oxaya-Altos de Pica Formations and the underlying red beds dated at 28±6 Ma in the Atacama district (TRAVISANY, 1978).

This tectonic pulse is also reported : in Colombia at about 24 Ma (DUQUE-CARO, 1976) ; in north-central Chile (29°-31°S) prior to 27 Ma (MAKSAEV *et al.*, 1984) ; and NW Peru (MACHARÉ *et al.*, 1986). In central Peru, its evidence is still unclear. Structural analysis performed in the Pacific Piedmont of southern Peru (SÉBRIER *et al.*, 1982 ; HUAMAN, 1985 ; MACHARÉ *et al.*, 1986) indicate a roughly NNE-SSW trending direction of shortening, i.e., approximately parallel with the upper Oligocene (between 26 and 28 Ma) direction of convergence (PILGER, 1983). This compressional phase corresponds thus with the beginning of the fast convergence period (Pilger, 1983) that extended up to upper Miocene time (ca 6-7 Ma) ; this latter period being coeval with an increase of volcanic activity. Due to its large areal extent and because it is clearly demonstrated on the Bolivian Altiplano we propose to name this upper Oligocene compressional tectonics : the Aymara phase.

The lower Miocene compressional tectonic pulse, F3 (ca 15-17 Ma)

This phase is presently poorly known because, either the unconformable overlying formations are imprecisely dated, or the reported unconformities are unclear. Whatever the case, structures related to this tectonic pulse (monoclinal folds and reverse faults) appear to be small and the main effect of this phase is exhibited by the evolution of landform (see section 5). In the Peruvian Pacific Piedmont, this phase is roughly coeval with the large valley incision that took place between the lower Miocene Huaylillas and middle-upper Miocene Chuntacala Formations (SÉBRIER *et al.*, 1979 and 1982 ; TOSDAL *et al.*, 1981 and 1984, HUAMAN, 1985).

In fact this valley incision corresponds to a major change : aggradation was previously the main landform process within the Pacific Piedmont whereas, erosion (i.e., uplift) has subsequently been the dominant one.

This compressional pulse should be (fig. 3) : (1) on the Pacific Piedmont bracketed between 14.2 and 17.6 Ma (SÉBRIER *et al.*, 1982) ; (2) in the Western Cordillera prior to the 15.8 Ma Tintinave ignimbritic tuff (SÉBRIER *et al.*, 1983) ; and (3) on the Peruvian Altiplano bracketed between 18 and 19 Ma (BONHOMME *et al.*, 1985a). In the Eastern Cordillera, the 15.9 ignimbritic tuff of the Crucero basin could be unconformable with the Caycone volcanics dated at 22.8 Ma (BONHOMME *et al.*, 1985b). This compressional event is bracketed : in south central Peru (12°-13°30'S), between 14 and 17 Ma (MÉGARD *et al.*, 1984) ; in north central Chile (29°-31°S), between 16.6 and 18.9 Ma (MAKSAEV *et al.*, 1984) ; and in central Chile (33°-36°S), between 14 and 21 Ma (DRAKE *et al.*, 1976 and 1982). In Colombia evidence exists for compressional deformations at about 15 Ma (DUQUE-CARO, 1974). Therefore this lower Miocene compressional event, appears to be bracketed between 15-17 Ma.

Middle Miocene compressional tectonic phase, F4 (ca 10 Ma)

As for the lower Miocene compressional pulse there is only little evidence for a middle Miocene tectonic pulse. In the Peruvian Pacific Piedmont (fig. 4), reverse faulting, affecting the Chuntacala Formation, are dated between 9.4 and 10.8 Ma (HUAMAN, 1985). Similarly in the North Chilean Longitudinal Depression (fig. 4), the Diablo Formation, dated at 9 Ma, rests unconformably on the Oxaya-Altos de Pica Formations dated between 15.5 and 23 Ma (MORTIMER *et al.*, 1974). The unconformity located between the Upper and Lower Tinajani (AUDEBAUD and VATIN-PÉRIGNON, 1974) should correspond to this tectonic pulse (fig. 3).

In central Peru this compressional pulse is dated between 9 and 10 Ma (MÉGARD *et al.*, 1984). Evidence of compressional deformations are also mentioned in Colombia (DUQUE-CARO, 1974) and in northwestern Argentina (ALLMENDIGER, 1986).

In the Pacific Piedmont of southernmost Peru, the middle Miocene phase is coeval with an erosional period that formed stepped pediplains (TOSDAL *et al.*, 1984 ; see section « Andean uplift »). Although the lower and middle Miocene compressional phases are poorly demonstrated it is unlikely that all the compressional deformations have been produced by a single tectonic phase. Nevertheless these two compressional pulses may be interpreted as climax events belonging to a Miocene period that would be characterized by compressional deformations. The few structural data on these two compressional pulses suggest that shortening was oriented roughly E-W (HUAMAN, 1985).

Late Miocene compressional tectonic phase, F5 (ca 7 Ma)

This late Miocene compressional phase is best dated on the Bolivian Altiplano where it took place between 7.4 Ma and 8 Ma (fig. 3 and 6). Elsewhere, it is also relatively well dated. It falls before 7.2 Ma in the Western Cordillera, 5.7 Ma in the Peruvian Altiplano and 3.9 Ma in the Eastern Cordillera. In the Pacific Piedmont and on the Pacific Coast it is placed before the Pliocene deposits (fig. 3). In the Sub-Andean zone, the reputedly Plio-Pleistocene Pagorene Formation is posterior to this phase.

This upper Miocene compressional pulse is reported along the whole Andean chain. It is dated at about 6-7 Ma : in Colombia (VAN HOUTEN, 1976), in central Peru (MÉGARD *et al.*, 1984 ; BONNOT, 1984), in northern Chile (LAHSEN, 1982), in the Argentine Puna (SCHWAB and LIPPOLT, 1974), and in Central Chile (DRAKE *et al.*, 1976 and 1982).

The Pacific Coast and Piedmont structures are represented by reverse and strike-slip faults, as also by monoclinal flexures. The Western Cordillera and the Altiplano are characterized by folds and by reverse and strike-slip faults. In the Eastern Cordillera mainly faults are observed, whilst in the Sub-Andean zone folds and thrusts predominate. As AUDEBAUD *et al.*, (1976) ; LAUBACHER (1978) ; MARTINEZ (1978) and SÉBRIER *et al.*, (1979) have already emphasized, this compressional tectonic phase displays a preponderance of faulting over folding. Structures associated with Late Miocene movements bear witness to the importance of strike-slip tectonics in the deformation of the High Andes continental crust.

Results obtained by structural analysis seem complex. According to FORNARI *et al.*, (1978) the compressional stress axis of this phase would be E-W trending in the Western Cordillera of South Peru. The same direction of shortening is proposed for the upper Miocene compressional deformations of the Peruvian Fore-Arc (HUAMAN, 1985 ; MACHARÉ *et al.*, 1986). They are thus identical to that found by SOULAS (1975) for this same phase, in Central Peru, to the North of the Abancay deflection. On the other hand, on the Bolivian Altiplano, the disposition of « en échelon » folds in the Miocene beds, with an average orientation of the axes of N110°E, along the San Andres fault striking N145°E is in agreement with a right lateral horizontal displacement related to an approximately N-S trending shortening. Similarly results from the Crucero basin (LAUBACHER *et al.*, 1987) suggests a N-S trending shortening. There are thus three possible interpretations : (1) Either, the stress pattern varies between the Western Cordillera of South Peru and the Bolivian Altiplano. (2) Or this phase is subdivided into two compressional pulses, N-S and E-W trending respectively. (3) Or this is a geometrical consequence of the Andean oroclinal bends, as we proposed for the early Quaternary tectonic pulses.

Late Pliocene-Early Quaternary compressional tectonic movements, F6 (ca 2 Ma)

This phase was first reported in Bolivia where it is prior to 2.5 Ma (EVERNDEN, 1966 ; MARTINEZ, 1980). Now it is known in virtually the whole Central Andes (SÉBRIER *et al.*, 1979 and 1982 ; SÉBRIER and MACHARÉ, 1980 ; BLANC, 1984 ; BONNOT, 1984 ; MALUMIAN and RAMOS, 1984 ; ALLMENDIGER, 1986 ; LAVENU, 1986). Nevertheless, in the Western Cordillera it is still not clearly characterized. Likewise in the Sub-Andean zone, it is often difficult to distinguish its effects from those of Late Miocene tectonics (fig. 3). However, in the southermost part of the studied region, these two tectonic phases have clearly been separated due to the occurrence of two angular unconformities of regional extent (AHLFELD and BRANISA, 1960).

The effects of these Latest Neogene compressional movements are generally local. In the Pacific Coast and Piedmont this compressional tectonics produced essentially monoclinal folds, reverse and strike slip faults and also warping. These kind of structures affect the marine Upper Pliocene and detritic Early Quaternary at Puente Hamani near to Pisco and also the continental Pliocene at Toran near to Camana (fig. 1). On the Altiplano, this tectonics has produced folds, reverse and strike slip faults. It affects the lacustrine Pliocene of Curahuara and La Paz regions and also latitic flows of the Puno region (Atuncolla fault, 20 km to the NW of Puno). In the Eastern Cordillera, these movements locally produced folds associated with reverse and strike slip faults. This is the case in the Cochabamba basin (LAVENU and BALLIVIAN, 1980) where the lacustrine Pliocene deposits are slightly folded. In the Sub-Andean foot-hills, these compressional movements mainly generated folds associated with reverse faults. During Upper Pliocene-Early Quaternary tectonic movements, strike-slip faulting has been the major deformational process of the High Andes crust, inducing thus slight local folding.

Wherever structural analysis has been performed, it indicates : (1) A roughly E-W trending compressional stress axis for the older and more extended pulse. Thus the major faults with an « Andean strike » (NW-SE) have tendency to left lateral horizontal displacement, e.j., the San Andres fault on the Bolivian Altiplano. (2) A roughly N-S trending compressional stress axis for the younger pulse. Thus the « Andean strike » faults have tendency to right lateral horizontal displacement ; e.j., the Laguna Pomacanchi fault located 60 Km to the SE of Cuzco (fig. 1). In the South-Peruvian Sub-Andean foot-hills, this pulse seems responsible of folding and faulting that correspond to a roughly N-S trending shortening (LAUBACHER *et al.*, 1984b ; SÉBRIER *et al.*, 1985).

In fact, the occurrence of two different kinematics may be due to a single discrete tectonic pulse during which the compressional stress axis alternates from N-S to E-W. As it is suggested by theoritical modelling of angular plate boundary (SHIMAZAKI *et al.*, 1978 ; KATO *et al.*, 1980) this alternation may result from the Andean oroclinal bends : the Santa Cruz (18°S) and Huancabamba (5°S) deflexions.

Subsequently, during Pleistocene time, a few compressional episodes occurred whose compressional stress axis would seem to be about NW-SE (LAVENU, 1978). Whatever the interest of these few compressional episodes, the conspicuous Pleistocene and Present tectonics is roughly N-S extensional (SÉBRIER *et al.*, 1985 ; LAVENU, 1986).

From Oligocene to Present, the observed structures emphasize the predominance of faulting and the occurrence of folding where the thickest series are located (fig. 10). In the Central Andes of South Peru, North Chile, and Bolivia, compressional deformations that occurred from Oligocene to Present would result from five discrete compressional tectonic phases. They are dated respectively from Upper Oligocene, Lower Miocene, Middle Miocene, Late Miocene and Upper Pliocene-Early Quaternary. Presented data could suggest that these *compressional tectonic phases could be short-lived, may be less than a million years each*, at least for the two most recent. This observation supports the idea of crisis in the geodynamic process and give evidence for change in the stress regime.

SEDIMENTATION AND TECTONICS

Throughout the whole studied period, the Andes display continuously the characteristics of a mobile zone. As a matter of fact there is a strong subsidence in the Altiplano basin, particularly during the Oligo-Miocene. The analysis of Coastal marine deposits, Western Cordillera volcanics, and Subandean continental deposits support also subsident conditions. In addition, uplifting areas are contemporaneous of the Cenozoic sedimentation ; the Eastern Cordillera, the boundaries between the Altiplano and the Western Cordillera, and between the Western Cordillera and the Fore-Arc. Tectonic activity occurs therefore between the discrete compressional pulses.

During Quaternary and Present, the Andean state tectonics is characterized by N-S trending extension in the High Andes and Fore-Arc, and by E-W trending compression in the Subandean Lowlands and at the contact between the Nazca and South American Plates (SÉBRIER *et al.*, 1982, 1985, and 1987 ; BONNOT, 1984 ; LAVENU, 1986 ; MACHARÉ *et al.*, 1986). During Pliocene, the same tectonic outlines prevail, but the extension is oriented between E-W and NE-SW (SÉBRIER *et al.*, 1982 ; BONNOT, 1984 ; LAVENU, 1986 ; MACHARÉ *et al.*, 1986). For earlier periods structural information is too scarce to establish what was the Oligo-Miocene state of stress between the compressional pulses. Sedimentological observations on the Andean basins provide only some suggestions.

The sedimentological records of the Andean basins show that their thicknesses, and consequently their subsidence rates, are highly variable (fig. 4, 5, 6, 7, and 9). The Fore-Arc basins are the less subsident (maximum being of the order of 1 mm per year), and they may be interpreted as slight crustal undulations caused by the shallower convex geometry of the Benioff zone (MACHARÉ *et al.*, 1986). The Subandean basins exhibit subsidence rates comparable to those of the Fore-Arc basins. However these Subandean basins correspond indeed to compressional Foreland basins. As other Foreland basins, they should be interpreted as resulting from lithospheric flexure due to thrust loading (DICKINSON, 1977). The High Andes

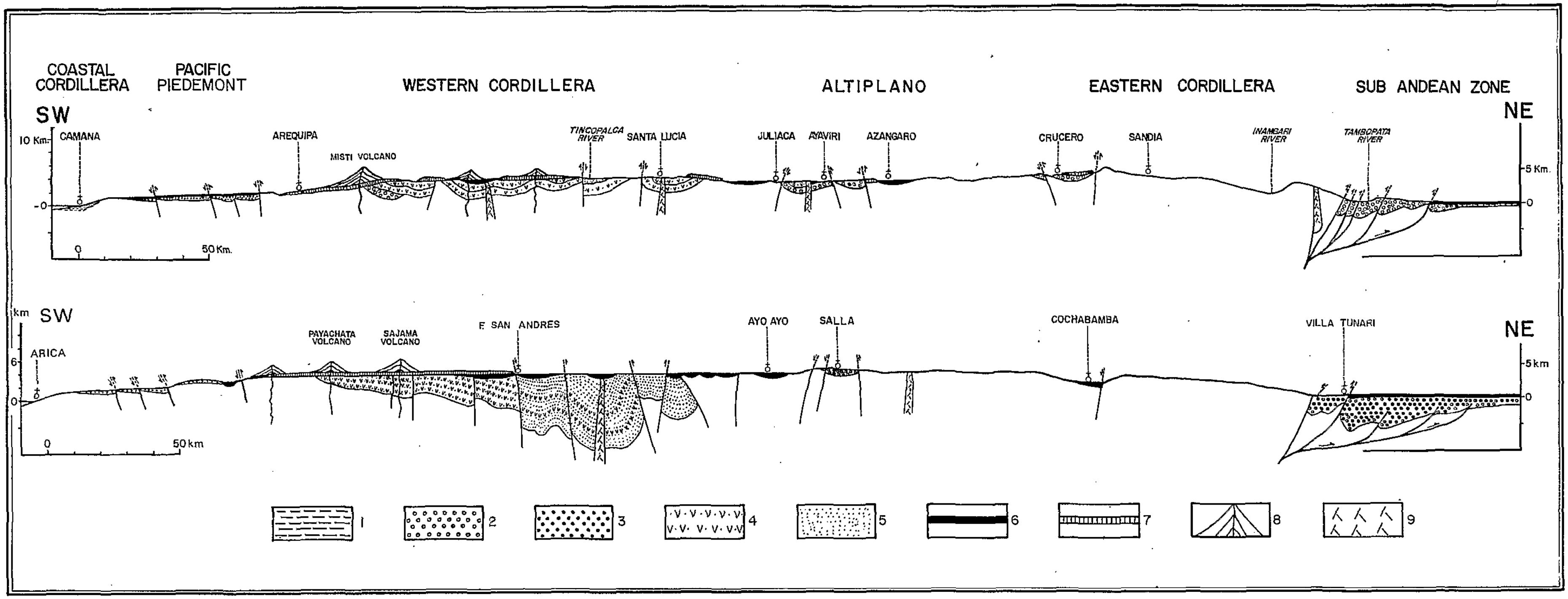

Fig. 10. — Synthetical geological profiles across the studied area. The upper one is located in southern Peru and the lower one in northernmost Chile and central Bolivia. 1 : Oligo-Mio-Pliocene marine sediments ; 2 : Oligo-Miocene continental detritic sediments ; 3 : Oligocene to Lower Miocene continental detritic sediments ; 4 : Oligo-Miocene volcanic and volcano-clastic sediments ; 5 : Miocene terrigenous and lacustrine deposits ; 6 : Pliocene conglomeratic and lacustrine deposits ; 7 : Plio-Pleistocene tuffs and lavas ; 8 : Quaternary volcanoes ; 9 : Oligo-Miocene intrusive bodies

basins have characteristics that vary according to their morphostructural locations. The small Eastern Cordillera basins are clearly exceptional and related to intracordilleran fault zones. Their tectonic regime may be interpreted as resulting either from normal faulting, as the Bolivian Cochabamba basins (LAVENU *et al.*, 1986), or from strike-slip faulting, as the South-Peruvian Crucero basin (LAUBACHER *et al.*, in press). The Western Cordillera basins are located within the magmatic arc. Although very thick series have been reported (3 000 m of Tacaza, according to NEWELL, 1949), they may not be indicative of rapid subsidence rates. In fact these thick volcanic series can be due to the pilling up of volcanic materials or to the infilling of canyon valleys blocked by volcanoes. The Altiplano basin exhibits the thickest sedimentary series ; during Oligo-Miocene time subsidence rate is at least of 0.5 mm per year and could reach 1 mm per year (LAVENU, 1986). It corresponds to a sedimentary trough located between the main magmatic arc (Western Cordillera) and the inner magmatic arc (Eastern Cordillera). However its origin is still unclear. Whatever the case, the strong Oligo-Miocene volcanic activity of the Western Cordillera and the high sedimentary accumulation of the Altiplano are likely to be related to a dominantly tensional stress regime due either to extensional (i.e., « rift » basins) or strike-slip (i.e., « pull-apart » basins) deformations.

MAGMATISM AND TECTONICS

In Central Andes, a strong volcanic activity has been occurring from Oligocene to Present. This magmatic activity is a conspicuous feature of the Andean chain. During Meso-Cenozoic evolution, a magmatic eastward migration is observed. Notwithstanding, it is not a continuous process. There are three locations for magmatic activity : Pacific Coast and adjacent Piedmont during Mesozoic till Upper Cretaceous, limit between Pacific Piedmont and Western Cordillera from Upper Cretaceous till Upper Eocene, Western Cordillera and Altiplano from Oligocene to Present. The jumps in the location of magmatism occurred roughly at the same time as the major compressional pulses : Peruvian phase (Upper Cretaceous) and Incaic phase (Upper Eocene). However, from Oligocene to Present, migration is not clearly observed with compressional tectonic phases. In fact, it seems that the volcanic activity points have a certain stability. Obviously some periods of more intense activity are known but are not well studied, they could be roughly limitated by the compressional phases. During Plio-Quaternary time, LEFEVRE (1979) has determined that the potash amount in volcanic rocks increases with the distance to the oceanic trench and the depth of the Benioff zone. Thus the volcanism is calc-alkaline in the Western Cordillera to shoshonitic in the Altiplano. The same observation seems to exist for Oligo-Miocene volcanism. In addition, a peculiar magmatism is found in the Eastern Cordillera (see section 1.5), it is characterized both by crustal and mantle derived volcanic and plutonic rocks (GRANT *et al.*, 1979 ; McBRIDE *et al.*, 1983 ; LAUBACHER *et al.*, in press).

The compressional tectonic phases appear to control the great features of magmatic evolution. In the studied zone, volcanic emissions occurred mainly between compressional pulses (fig. 3). However there is some evidence that volcanic activity can occur at the same time than compressional deformation as it is shown in the Ayacucho basin during the upper Miocene pulse (MÉGARD *et al.*, 1984). In the Altiplano and Eastern Cordillera the ages of batholiths or stocks support two periods of main intrusive activity : about 19 to 26 Ma and about 9 to 14 Ma (EVERNDEN *et al.*, 1966, 1977 ; AUDEBAUD *et al.*, 1979 ; GRANT *et al.*, 1979 ; McBRIDE *et al.*, 1983). Thus these intrusive activities extended out of compressional phases ; however they seems to initiate during compressional phases and to follow their intrusive process later.

The strong Oligo-Miocene magmatic activity of the High Andes is coeval with the 26 to 6 Ma period of fast convergence rate that is reported by PILGER (1983 and 1984). It is also contemporaneous with a period that is characterized by several compressional pulses (see section « Timing of compressional tectonic phases »). Conversely, during Quaternary and Pliocene Andean magmatism is clearly related with extensional tectonics (SÉBRIER *et al.*, 1985 ; LAVENU, 1986). Therefore, Andean magmatic activity can occur contemporaneously with both tensional or compressional deformations. In this late case, in fact compressional deformations may be due to strike-slip faulting and thus locally transtensional deformations should control volcanic emissions.

ANDEAN UPLIFT

In southern Peru and Bolivia northern Chile, the Andes form a high plateau whose average altitude is over 4 000 m. There are only a few summits of the Western and Eastern Cordilleras which overtop 6 000 m. Likewise, the Altiplano between these two cordilleras is itself at an average altitude of almost 4 000 m. Thus Central Andes exhibit a flat topography on their top. Early authors attributed this conspicuous feature, to a raised ancient morphological surface : this is BOWMAN'S (1916) Puna surface. From then questions began to be asked about how and when this Puna surface had been raised to more than 4 000 m. This has proved to be a very ticklish problem to solve because the Puna surface is polygenic (DOLLFUS, 1973). In the studied region remnants of volcanic plateau, evidence of ancient morphological surfaces, range in age from 53 Ma (MORTIMER, 1973) to Quaternary ! In addition, the initial altitudes of these surface are unknown, hence it is not possible to estimate the amplitude of uplift, and consequently its velocity. The commonly accepted idea is a very recent and still active uplift. Actually, this problem is better approached by the study of the Andean Piedmonts. The Amazonian lowlands are too eroded and too covered by the forest to allow detailed observations so that the desertic Pacific Lowlands are much more illustrative.

On the Coast and Pacific Piedmont, SÉBRIER *et al.* (1979 and 1982) have distinguished three flat paleotopographies : S1, S2 and S3. They are respectively attributed to Lower Miocene, Upper Miocene and Upper Pliocene-Early Quaternary. Each one is separated from the older one by a major incision of drainage (fig. 11).

S1 corresponds to an aggradational pediplain formed on the topmost surface of a Piedmont accumulation (Upper Moquegua Formation) covered by acidic tuffs (Huaylillas and Oxaya Formations, see 1.2 and fig. 4).

S2 corresponds to the top of wide paleovalleys fillings (Chuntacala Formation, see « The Pacific Lowlands ») or to the Tamarugal pediplain (Diablo Formation, see « The Pacific Lowlands »). S2 is incised roughly about 400 m into S1. In detail, S2 is formed by three stepped stages of alluvial deposits (TOSDAL *et al.*, 1984).

S3 corresponds to an aggradational pediplain formed on the top of valley fillings (Pliocene alluvial deposits). The difference of height between S2 and S3 is roughly of about 500 m. However the canyon incision posterior to S2 and prior to S3 is nearly 1 000 m deep.

The formation of these flat paleotopographies have required a relative tectonic stability. Between each one, it is necessary to produce a major incision, and thus a strong erosional event. This erosional event bears witness of a desiquilibrium in a fairly stable morphological system. It indicates therefore a rapid uplift of the Andean topography. This remarkable phenomenon is coeval with compressional tectonic phases (see sections « The Pacific lowlands » and « Timing of compressional tectonic phases ») : Middle Miocene (incision into S1), Late Miocene (incision into S2) and Pleistocene (incision into S3). The Andes have thus risen mainly during or slightly after each compressional pulse. The amount of uplift between two surfaces is equal at least to the difference of height between the older one and the bottom of the incision prior to the younger one. Thus the Middle Miocene uplift is at least 400 m, and the Late Miocene one is about 1 000 m. The Quaternary uplift is of the order of 200-300 m as shown by the altitude of Pleistocene marine terraces and present valleys incision in Pacific Piedmont.

From Middle Miocene to Present, SÉBRIER *et al.* (1979) have estimated a minimum average speed of uplift of 0.15 mm per year. However this rate does not take into account the discontinuity of the phenomenon, nor the probable subsidence of the Andes during certain periods. It is best then to try to estimate the average velocity of uplift pulses. The Late Miocene compressional tectonic phase is the only one which presently allow to do such an estimation. The compressional pulse occurred about at 7 Ma. Rather at the same time a strong uplift allowed a valley excavation at least to their present day level (SÉBRIER *et al.*, 1982). This incision took place very rapidly since it was completed, both in Peru and northern Chile, at the endmost Miocene, about 6 Ma B.P. (see section « The

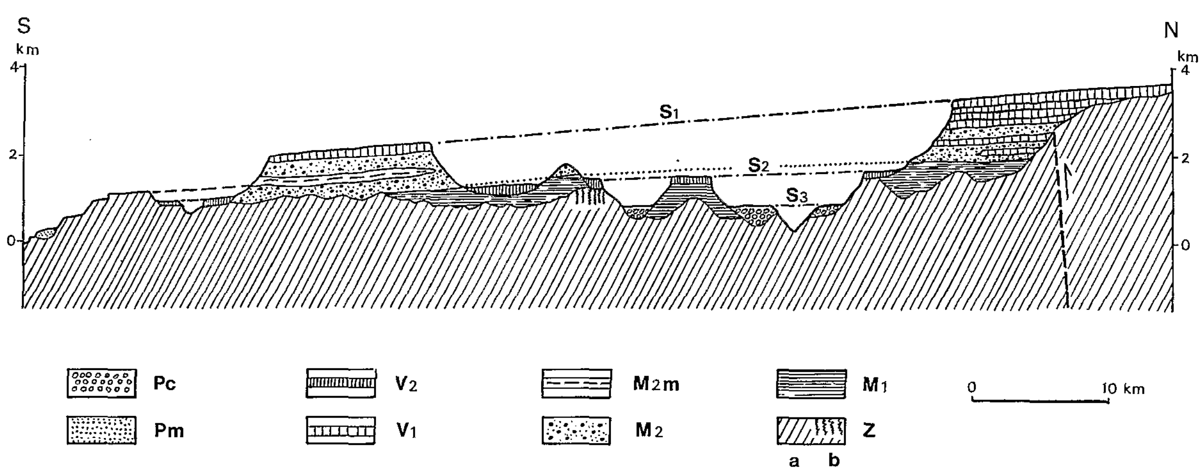

Fig. 11. — Morpho-stratigraphic sketch of southern Peru Andean Pacific Piedmont showing the Cenozoic morphological surfaces. S1, S2, and S3. Tectonic structures (faults and monoclinal folds) have not been represented. Pc : Pliocene conglomeratic deposits ; Pm : Pliocene marine sediments ; V2 : Upper Miocene acidic tuffs (Chuntacala Formation) ; V1 : Upper Oligocene-Lower Miocene acidic tuffs (Huaylillas Formation) ; M2 : Upper Oligocene-Lower Miocene continental sediments (Upper Moquegua Formation) ; M2m : Upper Oligocene-Lower Miocene marine intercalation of the upper Moquegua Formation ; M1 Oligocene continental sediments (Lower Moquegua Formation) ; Z : Pre-Oligocene substratum. Thick dotted line indicate the location of the fault zone limiting the Western Cordillera from the Piedmont

Pacific Lowlands »). Thus the available time for the incision is roughly 1 Ma. The amount of uplift being about 1 000 m in 1 Ma, the Late Miocene average uplift rate is 1 mm/year.

Using the Pacific Piedmont morphological surface it is also possible to have the order of magnitude of the minimum altitude of the Andes at the beginning of the Neogene. As we said S1 surface corresponds to an aggradational pediplain. Presently this kind of broad Piedmont pediplain has deposits slope angle which is roughly of the order of 1° or even less. In addition this pediplain was in relation with sea level as a marine intercalation is seen within the Upper Moquegua formation (see « The Pacific Lowlands »). Besides, analysis of the Coastal Cordillera scarp (SÉBRIER *et al.*, 1979 and 1982) indicates that the Miocene coastline was roughly nearby the present day one. Thus the length (L) of this pediplain, which can be followed up to the Pacific Coast, was at very least equal to the distance between the Pacific Coast and the Western Cordillera edge, that is to say 100 km. Therefore, the minimum height (Hm) at the level of the Western Cordillera can be estimated :

$$Hm \leq L.\ \mathrm{Sin}\ 1° \leq 2\,000\ \mathrm{m}$$

This shows that the Andes had already risen considerably and could not have been less than some 2 000 m high at about 17-20 Ma. This lower Miocene Andean topography should be due to the Paleogene geodynamic evolution.

Finally in Central Andes, two scales of vertical movements must be distinguished : (1)-Uplifting pulses that involve the whole of Andean Cordillera and are roughly coeval with compressional tectonic pulses. (2)-Differential vertical movements along Andean fault zones that are coeval with sedimentation and volcanic activity. The figure 12 illustrates these differential vertical movements and the minimum altitude of the Andes during three epochs : Lower Oligocene, Lower Miocene and Pliocene. The progressive uplift of Andean chain and the fact that the Eastern Cordillera has always behaved as a positive zone will be noticed.

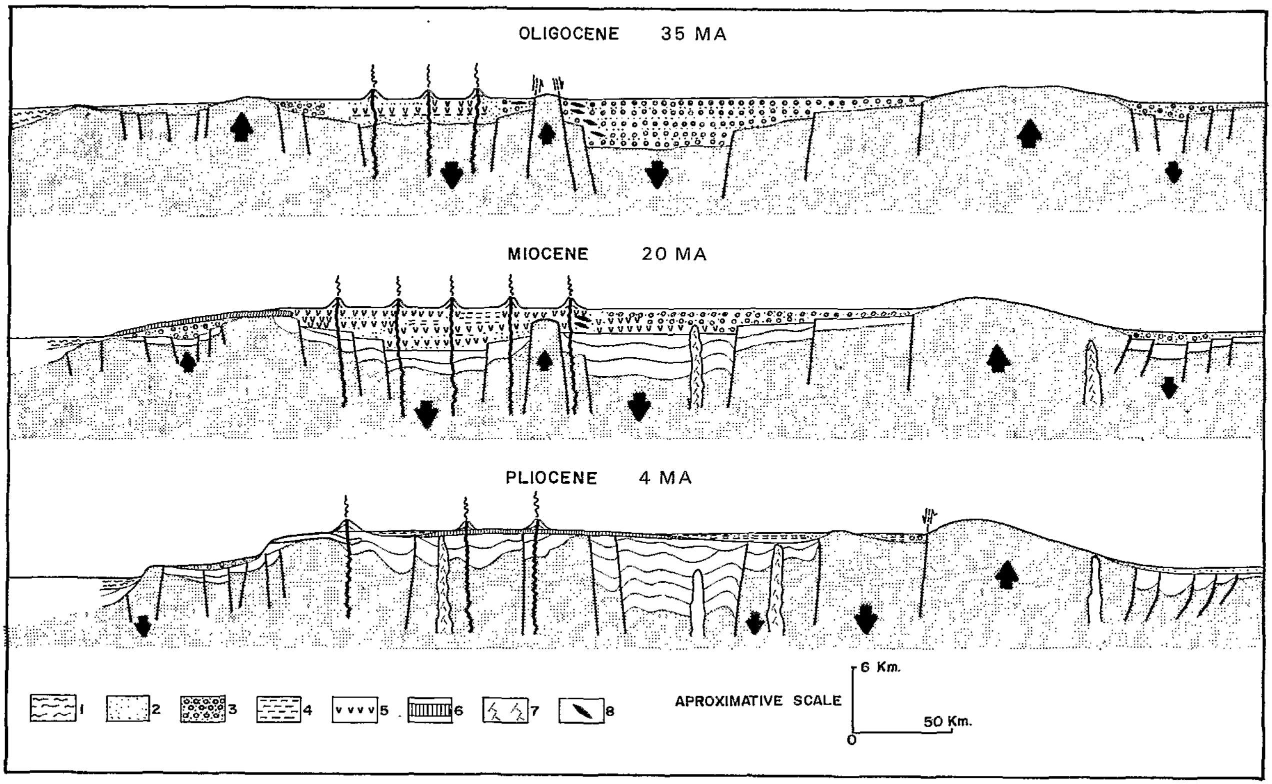

Fig 12 — Schematic profiles showing the Cenozoic evolution of Central Andes. 1 . marine sediments ; 2 : terrigenous continental deposits ; 3 continental detritic deposits ; 4 . lacustrine sediments , 5 : volcanic and volcano-clastic deposits ; 6 . volcanic deposits (tuffs and lavas) lying on morphological surfaces ; 7 : intrusive bodies , 8 olistolitic facies. Black arrows show differential vertical movements, size of arrows in relation with the estimated amplitude of vertical movements. Active faults coeval with sedimentation are indicated by a couple of thin half arrows. Stippled area for pre-Oligocene substratum.

CONCLUSIONS

In southern Peru, Bolivia, and northern Chile, field observations and re-evaluation of the geological data allow to establish the chronological evolution of the Andean morphostructural zones and to correlate them. This analysis gives evidence for six discrete compressional tectonic pulses that are dated respectively : upper Eocene (ca 42 Ma), upper Oligocene (ca 26-28 Ma), lower Miocene (ca 15-17 Ma), middle Miocene (ca 10 Ma), upper Miocene (ca 7 Ma), and early Quaternary (ca 2 Ma). These discrete pulses appear to correspond to high convergence rate periods (fig. 13). Available structural data on these compressional phases suggest their shortening direction is roughly parallel to the convergence orientation. Basinal infillings are highly variable. They are in agreement with the various processes that may put forward to explain the formation of Andean basins. These basins are preferentially compressional in the Subandean Lowlands and mainly tensional in the High Andes and Pacific Lowlands. Magmatic activity is located in the High Andes since at least upper Oligocene (ca 26 Ma). It is coeval both with compressional and extensional deformations. In Central Andes, this magmatic activity is maximum between 26 and 6 Ma, i.e., contemporaneously with the Miocene period of high convergence rate (fig. 13). It appears thus that the magnitude of magmatic activity is related with the convergence rate. Observations performed on the Neogene morphological surfaces show clearly that the high cordilleran topography has been formed between roughly 26 and 6 Ma, i.e., during the period of Miocene high convergence rate and strong magmatic activity. These morphological data indicate also that the uplift of Central Andes has been produced by discontinuous event that are coeval with the discrete compressional tectonic phases. This Andean uplift is old in part, as at the end of Miocene, the present-day altitude had rather been reached. All these data are thus in agreement with the fact that the Western Cordillera uplift is due to a crustal thickening which has been produced both by tectonic shortening and by magmatic accretion.

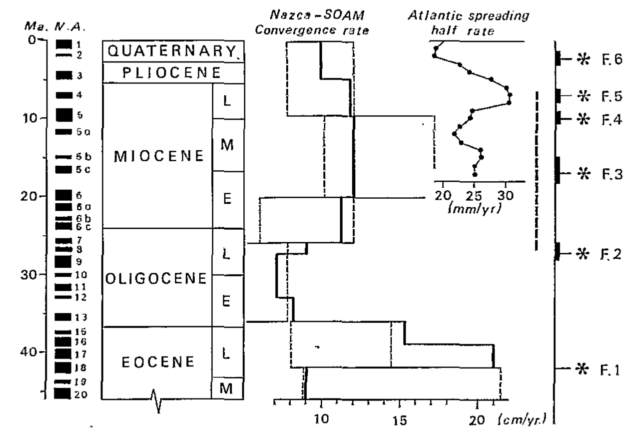

Fig. 13. — Chronology of compressional events, F1 to F6, that have affected Central Andes since Late Eocene time. Vertical thick segments show the time-ranges of these tectonic events. Convergence rate between Nazca and South American plates *from* PILGER (1983), space between dotted lines represents uncertainities on convergence rate calculated by PARDO-CASAS and MOLNAR (1987). Equatorial Atlantic half spreading rate *from* BROZENA (1986). Thick dashed line indicates the period of high arc magmatic activity. Magnetic anomalies and chronostratigraphy *from* BEGGREN *et al.* (1985).

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