NAZCA SLAB RETREAT VERSUS COMPRESSIONAL DEFORMATION IN THE CENTRAL ANDES SINCE LATE OLIGOCENE TIMES

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Resumé

Dans les Andes Centrales, les déformations compressives sont essentiellement le résultat d'évènements "brefs" qui séparent des périodes de relatif calme tectonique. Ces évènements correspondent à des instabilités dans la dynamique de la subduction andine qui semblent contrôlées par des arrêts de la migration de la fosse océanique vers l'Ouest.

Key words : Cenozoic, Central Andes, slab retreat, subduction, tectonics.

Introduction

In Central Andes, both seismological and neotectonic observations indicate that most of the present-day deformation is compressional and occurs on both sides of the Andes, i.e., in the fore-arc and the retroarc sub-Andean zone. The Andean Cordillera itself is very weakly seismic. Field observations allow the observation of Recent and active crustal deformation within the High Andes. Most of the active faulting is roughly located along the fault system that limits the High Plateaus from the Cordillera Oriental; some occurs within the Cordillera Occidental or, in southern Peru, along the limit between the Cordillera Occidental and the Andean fore-arc. Most of the crustal deformation is characterized by normal faulting, except within the Cordillera Oriental of central Peru which is located above a flat-lying slab segment. Thus, the High Andes and the Pacific Lowlands are characterized by roughly N-S trending extension and are bounded on both sides by compressional belts with a roughly E-W trending compressional regime. This state of stress may be explained as the interaction between the boundary forces due to the convergence between the Nazca and the South American plates and the body forces due to topography.

While subduction has been a continuous process since late Oligocene times, compressional deformations appear mainly to have occurred during short-lived events. This apparent discrepancy may be explained by variations in the oceanic slab retreat.

Main tectonic features of the Central Andes since late Oligocene times

Since at least 26 Ma, Andean deformations have occurred within a morphostructural framework roughly similar to the present-day one, and the sub-Andean Lowlands have acted nearly continuously as a retroarc foreland, where most of the Andean shortening has been accomodated by underthrusting of the Brazilian shield beneath the Cordillera Oriental. In contrast, the High Andes and the Pacific Lowlands are generally much less deformed than the sub-Andean retroarc foreland. One of the major problem which is still in debate is to determine whether or not Andean tectonics has been continuous there. The observation, at a regional scale, of roughly synchronous angular unconformities first suggested that tectonics had been characterized by short-lived tectonic phases, separating periods of tectonic quiescence. More recently, the continuity of the subduction process, and the observation of syndepositional folding led some authors to consider that tectonic phases corresponded to long-lived periods of compressional deformations in the whole Andean domain, and that the short-lived, generalized compressional tectonic events were only climax pulses within a continuum of deformation. Direct and indirect evidences for discontinuous tectonic events, responsible for faulting, folding, erosion and subsequent unconformities, do exist in the High Andes and the fore-arc basins. For the last 5 to 6 My, successive compressional and extensional deformations have been observed both in the intra-cordilleran and fore-arc basins of Peru and Bolivia (discussion and references in Mercier et al., 1990). Moreover, Cenozoic angular unconformities are accurately dated at some places, with time-span of approximately 1 My. In many localities however, these unconformities are less accurately bracketed, but all available data are in agreement with the hypothesis that each Andean angular unconformity is regionally of the same age. Indirect evidence for discontinuous tectonic processes is provided by the Cenozoic evolution of the Central Andean landscape, i.e. the development of regional morphological surfaces corresponding to long periods of relative stability, separated by pulses of rapid valley incision that are interpreted as consequences of short-lived periods of Andean uplift. This Andean uplift occurred mainly during Miocene times and developed through discontinuous pulses.

In the Central Andes, five generalized compressional tectonic events are evidenced during the relevant period. They are late Oligocene (Aymara - F2 - ca. 26 Ma)), early Miocene (F3 - Quechua 1 - ca. 17 Ma), middle Miocene (F4 - Quechua 2 - ca. 10 Ma), late Miocene (F5 - Quechua 3 - ca. 7 Ma), and latest Pliocene-early Pleistocene (F6 - ca. 2 Ma) in age respectively (discussion and references in Sébrier et al., 1988).

Syndepositional folding and faulting have been observed in several intra-cordilleran basins. A careful and critical examination of the few localities where folding and faulting is reported during intra-cordilleran sedimentation, suggests that each example of progressive compressional deformations may correspond to a detailed record of one of the generalized compressional events.

The deformations, either shortening or stretching, appear generally to be very weak between two generalized compressional tectonic events. In the sub-Andean retroarc foreland, available geological data are in agreement with a roughly continuous compressional regime during the last 26 My, with a probable exception during the Pliocene. In this region, shortening occurs on thrust faults with slip rates of the order of 1mm/year. Conversely, in the High Andes and Pacific Lowlands, available data suggest that between the generalized compressional events extensional tectonic activity prevails, this being clear for the Pliocene to Present period. This extensional tectonic activity did not produce significant stretching of the High Andes; in southern Peru, stretching is less than 1% during the last 2 My. Extensional tectonic activity also has been observed locally during the Miocene and throughout the Central Andes during the Pliocene. Miocene extensional tectonic activity is reported within some northern Peruvian basins. There are still few data however on the Miocene tectonic regime that characterized the intra-cordilleran basins; in particular, the deformations that are coeval with the thick continental series of the Miocene Altiplano are only hypothetically considered as due to normal faulting. Pliocene extensional tectonic activity is well documented. It produced many intra-cordilleran graben basins, such as the Callejon de Huaylas and the La Paz basin. This Pliocene extensional tectonic activity also has been observed along some fore-arc basins. Moreover, it could also be present within the sub-Andean retroarc foreland. If so, it appears that the whole Andean domain would have been submitted to extensional deformation during the Pliocene.

Relations between tectonic regime and plate dynamics -
Nazca slab retreat versus Andean deformation

Since late Oligocene times no major changes have occurred in the dynamics of the South Atlantic expansion. The western half-rate of expansion has varied between 20 and 30 mm/year during this period. For the interaction between South America - Nazca (Farallon) plates, the relevant time span may be divided within two main periods :

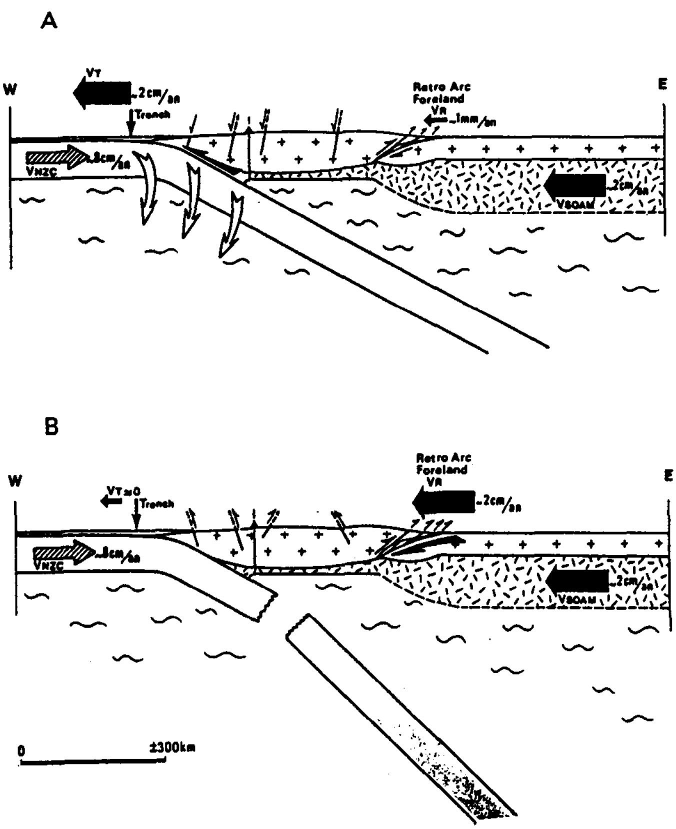
(1) Between 30 and 26 Ma, a major reorganization of plate dynamics in the eastern Pacific Ocean took place and the convergence rates has been very low untill the breaking up of the Farallon plate into the Nazca and Cocos plates at ca. 26 Ma. Oligocene tectonic activity is still poorly known, but it may be inferred that no major deformation, neither compressional nor extensional, occurred during this period.

(2) For the last 26 My the convergence has been characterized by high rates (mean rate of 11.0 ± 0.8 cm/year), a direction nearly orthogonal to the Peru-Chile trench (whith variations less than ±10° from the present-day direction), and a lithospheric age of the slab at the trench in the range 35 - 65 My. The only singular event during this period is the arrival of the Nazca ridge at the Peru-Chile trench at ca. 4 Ma, causing shallowing of subduction in central Peru.

During this period, the Andes have experienced a general compressive regime that appears to have been nearly continuous in the sub-Andean retroarc foreland. As the short-lived generalized compressional tectonic events occurred between longer periods of relative tectonic quiescence, they should correspond to inestabilities of a steady-state tectonic regime. The state of stress within the Andean Cordillera should be controlled by the balance between boundary forces, that are due to convergence, and body forces due to topography. As the High Andean Cordillera was mainly uplifted during the Miocene no major variation of body forces may be invoked to explain the Pliocene to present-day evolution of the Andean state of stress. Even during the last 26 My, rapid lowering of mean Andean elevation is not observed. Thus the compressional events should be mainby related to variations in the boundary forces. In some cases, these variations in the boundary forces are detected by variations in the Andean convergence rate, i.e. by far-field changes at the East-Pacific and Atlantic spreading systems. The late Oligocene F2 compressional event appears to be coeval with the increase in convergence rate and the change in the direction of convergence that followed the break-up of the Farallon plate. The latest Miocene F5 event would also correlate with a period of high spreading rate in the Equatorial Atlantic Ocean. The other generalized compressional events however do not appear to correlate with variations in the boundary forces related to changes in the convergence rate.

We hypothesize (Sébrier and Soler, 1990) that these generalized compressional events may be linked to instabilities of the dynamic equilibrium between the westward motion of the Andean lithosphere and the slab retreat of the Nazca lithosphere. During the intervals separating two generalized compressive events the retroarc Andean foreland, where virtually all the continental crustal deformation is concentrated, would be characterized by a thrust rate of the order of 1mm/year as the present-day one. Since in an absolute mantle reference frame the westward motion of the Brazilian shield is ca. 2 cm/year, this implies that during the tectonically "quiet" periods most of the westward drift of the South American plate is accomodated by an absolute westward overriding of the continental plate over a retreating Nazca slab (Figure). Accretionary prism is very poorly developped along the Central Andean margin, and tectonic erosion of the Andean margin has been invoked. However, the stable geometry of the fore-arc basins since the late Eocene suggests that tectonic erosion has not been a major process since 26 Ma. Available data on the retroarc Andean foreland indicate that during a generalized compressional event, the rate of thrusting should be of the order of at least 1 cm/year. During these events, compressive deformations also affected most parts of the Andean Cordillera. Thus during the compressive events virtually all the westward drift of the South American plate is accomodated by the tectonic shortening of the Andes, and consequently the western continental margin of the South American plate is virtually motionless in an absolute reference frame and there is no slab retreat (Figure). Then we interpret the generalized compressive events as recurrent instabilities due to the blocking of the retreat of the oceanic slab. Conversely, the periods of E-W trending extensional tectonics, as the one observed during the Pliocene, suggest a drastic decrease of the boundary forces. Such a "collapse" of the boundary forces should correspond to periods when the slab retreat tends to be faster than the westward motion of the South American lithosphere. Therefore the slab retreat could be the major process that has controlled the Andean tectonics at least during the last 26 My. Although the mechanism of slab retreat is not yet clearly understood, it may be inferred that a rapid blocking of the slab retreat would be correlated with a slab rupture.

Longitudinal variation of the slab retreat velocity may also explain the development of the Bolivian orocline. Once the orocline initiated, the slab retreat should become more difficult in that part of the margin where the slab as a strong concavity than in those segments where the margin is roughly linear. Consequently, the high retroarc shortening in the Bolivian orocline should correspond to this relatively slow slab retreat in the Arica elbow. Finally, the slab retreat may also explain the somewhat unstable stress regime that is observed during most of the generalized compressional events (i.e. dominant roughly E-W compression, parallel to the convergence, followed or accompanied by roughly N-S compression). The blocking of slab retreat and the associated breaking-off of the slab is unlikely to occur strictly at the same time all along the Andean margin. Thus, the longitudinal variations in the blocking of slab retreat may induce the observed unstable stress pattern.



Generalized sketch of subduction dynamics in the Central Andes since late Oligocene times

A- Steady-state situation, where most of the westward movement of the South-American plate (V_{SOAM}) is accomodated by the retreat of the Nazca slab (i.e., the westward migration of the trench, $V_T \approx V_{SOAM}$). The retroarc shortening (V_R) is weak. Extensional tectonic regime prevails in the High Andes and the Pacific Lowlands.

B- Situation during a short-lived generalized compressional event. Most of the westward movement of the South-American plate (V_{SOAM}) is accomodated by the retroarc shortening ($V_R \approx V_{SOAM}$); the retreat of the Nazca slab is weak or even blocked (i.e., the westward migration of the trench $V_T \approx 0$), and the slab is broken. Shortening also affects the High Andes and the Pacific Lowlands.

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