High-level surfaces, plateau uplift, and foreland development, Bolivian central Andes

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ABSTRACT

Newly dated Tertiary strata in the Bolivian central Andean plateau and synthesis of the Tertiary record in the adjacent Subandean fold-thrust belt constrain the age of deformation in both regions. Age of deformation within the plateau is determined by dated crosscutting relations associated with a regionally extensive high-level surface known as the San Juan del Oro surface. New ^{40}Ar-^{39}Ar dates on undeformed strata above the high-level surface preclude significant upper-crustal shortening within the Eastern Cordillera after 10 Ma. Tertiary strata within the adjacent Subandean region demonstrate that formation of the fold-thrust belt occurred after 10 Ma. On the basis of these data, we propose a two-stage model of late Cenozoic Andean growth that links plateau uplift to the development of the fold-thrust belt. In the first stage, early plateau uplift occurred in response to widespread compressional deformation of the plateau (Eastern Cordillera and Altiplano). During the second stage, beginning after 10 Ma, upper-crustal deformation within the plateau terminated, and the Subandean fold-thrust belt developed. Crustal-scale eastward thrusting along the eastern margin of the Eastern Cordillera drove Subandean folding and thrusting; the Eastern Cordillera served as the "bulldozer" for the deforming Subandean wedge.

INTRODUCTION

The evolution of high plateaus at convergent margins, typified by the central Andean and Tibetan plateaus, is one of the fundamental problems of continental tectonics. Early models of central Andean uplift by crustal thickening due to magmatic addition (e.g., Thorpe et al., 1981) have given way to models that emphasize crustal shortening. Isacks (1988) argued that uplift of the central Andes occurred in two discrete stages and was related to important paleotectonic controls. Deformation shifted to the foreland fold-thrust belt before the plateau reached its present limiting height, and deformation within the fold-thrust belt was directly linked to plateau uplift by shortening and thickening within the lower crust.

This paper presents new data that support the two-stage model. A new ^{40}Ar-^{39}Ar geochronology for an extensive high-level surface brackets deformation in the plateau. Independently, Tertiary strata in the Subandean fold-thrust belt limit the timing of deformation there. Sequential, balanced cross sections constrained by the new dates and available geologic and geophysical information illustrate the linkage between plateau uplift and fold-thrust belt development.

REGIONAL SETTING

The study area is located over a moderately dipping segment of the subducted Nazca plate in Bolivia. This area includes part of the Altiplano, the Eastern Cordillera, the Subandean fold-thrust belt, and part of the foreland basin (Fig. 1). The Altiplano and most of the Eastern Cordillera, which are defined as tectonic units (Pareja et al., 1978), lie within the larger physiographic region of the central Andean plateau (Isacks, 1988). The major bounding structures are (1) a west-vergent fault system, including the Falla San Vicente (Baby et al., 1990), which bounds the western side of the Eastern Cordillera; (2) an east-vergent fault system associated with the Principal Frontal thrust, which bounds the eastern side of the Eastern Cordillera (Baby et al., 1992); and (3) the deformation front, which separates the fold-thrust belt from the foreland basin (Pareja et al., 1978). Across the belt of rugged topography between the plateau edge and the Principal Frontal thrust, average elevations drop from 3–3.5 km to ~1.5 km; tributaries of the Pilcomayo and Río Grande rivers drain the Eastern Cordillera through this belt in canyons that reach depths of 1.5 km. The Principal Frontal thrust marks a distinct change in morphology from rugged, deeply incised topography to the valley-and-ridge topography of the fold-thrust belt. The geology and geologic history of this region are summarized in Ahlfeld and Branisa (1960), Martinez (1980), and Sempere et al. (1988).

SAN JUAN DEL ORO SURFACE

The San Juan del Oro surface (Servant et al., 1989) is a regionally extensive, widely recognized, high-level geomorphic surface that covers a large part of the Eastern Cordillera (e.g., Servant et al., 1989; Satoh, 1982; and Lavenu, 1986). From our field studies and satellite image interpretation, we recognize the San Juan del Oro surface as a composite landform composed of three discrete surface types: low-relief erosional uplands (type 1), coalesced pediments (type 2), and a prominent unconformity beneath undeformed Tertiary clastic deposits and giant ignimbrite sheets (type 3) (Fig. 1). Types 1 and 2 are geomorphic surfaces, and type 3 is their laterally equivalent unconformity.

The age control for the unconformity (Fig. 1) includes new ^{40}Ar-^{39}Ar dates and dates compiled from the literature. Near 18°S, the unconformity is bracketed between 18 and 8 Ma. Near 21°S, the unconformity is bracketed between 13 and 9 Ma. These time intervals bracket a phase of deformation and erosion. The 8 to 5 Ma Morococala, Frailes, and Panizos ignimbrite sheets overlie the unconformity and extend over an area of ~10 000 km^2 (Fig. 1).

Where not covered by ignimbrite sheets, the type-3 surface is covered by coarse clastic material. The 0–250-m-thick series of conglomerate, sandstone, and claystone beds was deposited in north-trending basins with longitudinal paleocurrent directions. The pediments (type-2 surface) lie along the basin margins. They are subplanar bedrock surfaces that truncate deformed Ordovician and Cretaceous strata. In their upper parts, the pediments are continuous with the smooth, gently rolling topography of the type-1 low-relief upland surface. The upland surface (type 1) is characterized by relatively smooth and rounded slopes, compared to the rugged, angular slopes of the dissecting canyons. Because the pediments commonly do not exhibit clear nickpoints at the margins of the upland surface, the two surface types are mapped together in Figure 1.

The erosional surfaces and overlying clastic deposits collectively define a landscape that evolved by processes of erosional smoothing and aggradation (cut and fill). As local deformation waned, aggradation began in shallow basins and pediments formed on their margins. Over time, uplands were erosionally smoothed, pediments expanded and beveled uplands, and basins expanded over and buried pediments. This evolutionary sequence, beginning after 10 Ma, characterizes widely separated exposures of the San Juan del Oro surface and suggests that discrete erosion surfaces expanded and coalesced into larger units over time. Thus the San Juan del Oro surface is time-transgres-

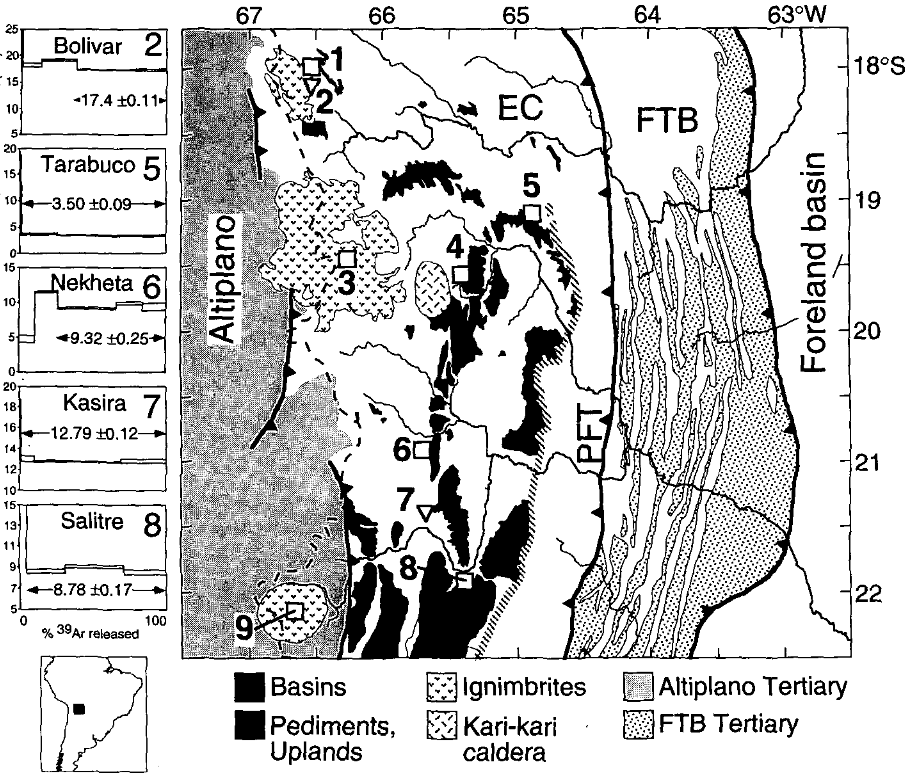

Figure 1. Simplified tectonic map of part of Bolivia. Lower Paleozoic strata of Eastern Cordillera (EC) are white areas between Altiplano and Principal Frontal thrust (PFT); within Subandean zone, white denotes Devonian through Cretaceous units. FTB = fold-thrust belt. Type 1 and type 2 surfaces (pediment and upland) are mapped together, and type 3 surfaces are subdivided according to kind of cover (ignimbrites vs. clastic-filled basins). Dashed line represents principal drainage divide; diagonal-rule line marks eastern edge of central Andean plateau where well-defined south of 19°S. Squares represent undeformed strata overlying surface; inverted triangles represent deformed strata cut by surface. At left are ^{40}Ar-^{39}Ar spectra and plateau ages for our sample sites 2 and 5–8; arrows indicate width of plateau. In all cases, minerals used for dating consist of fresh unaltered biotites separated to better than 99% purity from crystal-rich unwelded air-fall tuffs, except for Kasira sample, which is welded; no evidence of Ar loss or excess was observed. Compiled age determinations include Morococala ignimbrite—8.4 to 6.4 Ma (sample 1, ^{40}Ar-^{39}Ar) (Luedke et al., 1990), Frailes cover ignimbrite—8 to 5 Ma (sample 3, K-Ar) (Schneider and Halls, 1985), Chinoli Tuff—1.9 ±0.1 Ma (sample 4, ^{40}Ar-^{39}Ar) (Servant et al., 1989), and Panizos ignimbrite—7.9 to 6.7 (sample 9, ^{40}Ar-^{39}Ar) (Ort, 1992). Complete analytical data are available on request from Farrar.

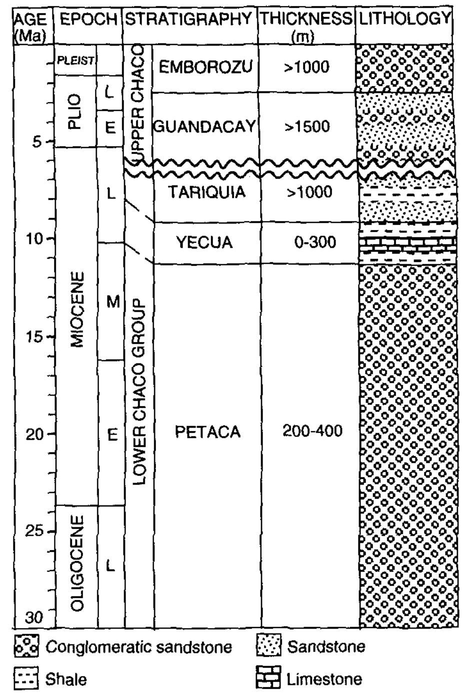

Figure 2. Simplified stratigraphic column of Subandean Tertiary. Thicknesses and lithologies are based on field observations and unpublished industry stratigraphic data from fold-thrust belt and foreland basin. Geochronology is as summarized in Marshall and Sempere (1991). Yecua Formation is interpreted to have been deposited during transgression of Paranense epicontinental sea into Subandean region during Miocene (10 Ma) marine highstand (Haq et al., 1987). Unconformity above Tariquía Formation is intra-Chaco discordance (Padula, 1959).

sive, but is everywhere younger than 10 Ma (Fig. 1). The development of this landscape ended with the onset of regional canyon incision during the Quaternary (Servant et al., 1989; Gubbels et al., 1991).

All three surface types and the overlying clastic deposits and ignimbrite sheets are almost entirely undeformed. Field mapping, careful examination of both monoscopic and stereoscopic satellite imagery, and review of the literature indicate that these surfaces are not deformed by compressional structures anywhere within the Eastern Cordillera. They are cut only by minor normal and strike-slip faults in a few places. Near 22°S, faults with 5–25-m-high scarps cut both the pediments and the upper aggradational surfaces of the basins (Cladouhos and Allmendinger, 1991). In the area of the ignimbrite sheets, cooling units overlying the unconformity are deformed only by normal faults of small displacement, some of which are probably associated with caldera collapse (Baker, 1981).

The part of the San Juan del Oro surface represented by the subignimbrite unconformity is the only area where the paleotopography was not modified as it was buried. The low relief exhibited by the subignimbrite unconformity indicates that the paleotopography was smoother and had a lower relief than the present, canyon-incised topography of the Eastern Cordillera. Throughout this region, the topographic relief exhibited by the San Juan del Oro surface can be entirely attributed to geomorphic processes of erosion and pedimentation rather than to post–10 Ma structural displacement. Thus, the preserved remnants of the San Juan del Oro surface can be considered discrete, dated structural datums that extend across the entire width of the Eastern Cordillera except for its rugged eastern edge (Fig. 1). The large areal extent of individual dated remnants, and the relatively uniform distribution of these undeformed remnants across approximately one-third of the area of the Eastern Cordillera west of the plateau edge, provides strong evidence against interpretations involving major compressional deformation within this region after 10 Ma.

SUBANDEAN FOLD-THRUST BELT AND FORELAND BASIN

The conventional interpretation that development of the fold-thrust belt began in the late Miocene or Pliocene (e.g., Ahlfeld and Branisa, 1960; Mingramm et al., 1979; Martinez, 1980; Jordan and Alonso, 1987) is based on the Tertiary stratigraphic record (Fig. 2). Throughout most of the fold-thrust belt, the Tertiary section appears to be folded concordantly with the underlying strata. The lack of angular unconformities between the Tertiary and the underlying Cretaceous and within the Tertiary on the flanks of the folds indicates a lack of pronounced early-formed structures. A post–middle Miocene onset of deformation is further supported by the fact that neither the Petaca Formation nor the Yecua Formation

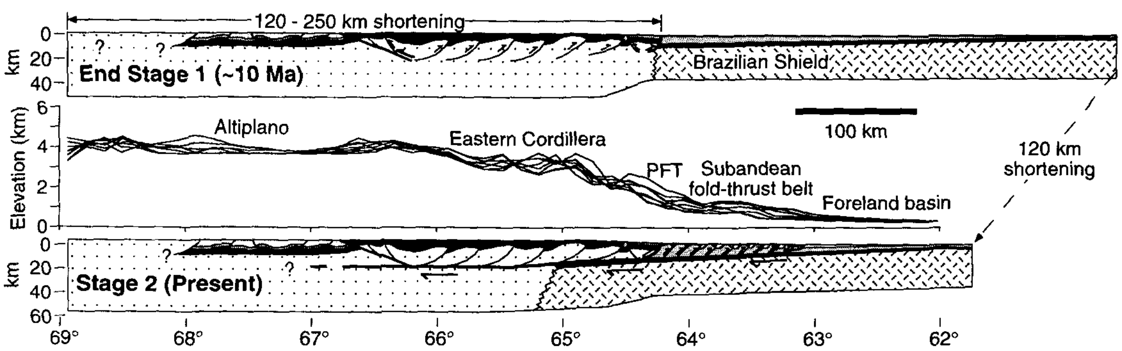

Figure 3. Two-stage model of plateau growth. Sequential, balanced crustal sections (no vertical exaggeration) across Andes at 20°S show region between magmatic arc and basement high on Brazilian shield. Black is Ordovician; dark shading is Silurian through Cretaceous; light shading is Tertiary. Initial crustal thickness is 35 km. Net shortening of 120 km during the past 10 m.y. is based on estimates discussed in text; however, shortening between late Oligocene onset (Sempere et al., 1990) and 10 Ma is poorly known. A maximum estimate of 250 km has been arbitrarily chosen to reflect additional amount of shortening required to reach minimum present crustal thickness of ~60 km. PFT = Principal Frontal thrust. Topographic profiles derived from digital topography are described in Isacks (1988). Eight individual east-striking profiles are centered on 20.0°, 20.2°, 20.4°, 20.6°, 20.8°, 21.0°, 21.2°, and 21.4°S and represent averages of 40-km-wide overlapping east-west swaths smoothed using 15-km-wide, along-strike moving window.

(Fig. 2) displays significant facies or thickness variations across the folds. In addition, the fine-grained nature of the Yecua Formation and the interbedded marine limestone layers provide evidence against significant uplift of the Subandean anticlines during deposition of the unit (~10 Ma; Marshall and Sempere, 1991). Thus, significant deformation within the fold-thrust belt did not begin until after 10 Ma. Either the intra-Chaco discordance (Padula, 1959) or the deposition of the Tariquía Formation may mark the onset of foreland folding and thrusting; both of these events are younger than 10 Ma (Fig. 2).

DISCUSSION

The chronology presented above supports the two-phase model of central Andean evolution (Isacks, 1988). A refined two-phase model incorporating these data is presented in the form of sequential cross sections in Figure 3. This model assumes that plateau uplift is due to crustal shortening and thickening and excludes the poorly determined effects of magmatic contribution to the crust, as well as uplift due to lithospheric thinning. We exclude these effects only for the sake of simplicity and recognize that other models are possible.

The extent of the region deformed during phase 1 was determined by paleotectonic controls. In contrast to the Brazilian Shield crust, the crust of the Eastern Cordillera and Altiplano is known to have been affected by at least two Paleozoic compressive deformations, as well as by Mesozoic extension (Mpodozis and Ramos, 1989; Sempere et al., 1988; Riccardi, 1988). An abrupt lateral change in sub-Cretaceous relative structural level in the vicinity of the Principal Frontal thrust provides strong evidence for the ancestral crustal boundary there. Cretaceous strata are underlain by upper Paleozoic units (Carboniferous and Permian) within the Subandes, but are underlain by deformed lower Paleozoic strata (Ordovician to Devonian) within the Eastern Cordillera and Altiplano. Contrasting structural styles, related to these paleotectonic controls, also distinguish the Eastern Cordillera from the Subandean zone. The regularity of fold wavelength, along-strike continuity of structures, and regionally consistent eastward structural vergence of the Subandean folds (Pareja et al., 1978) are characteristic of the classic "thin-skinned" style of compressional deformation (Dahlstrom, 1970). In contrast, structures within the Eastern Cordillera generally have steeper dips, irregular spacing and geometry, and variable vergence, and they commonly reactivate structures formed during earlier deformations.

In the first phase (pre–10 Ma), beginning in the late Oligocene (Sempere et al., 1990), crustal shortening was distributed between the magmatic arc and the Principal Frontal thrust, in the Eastern Cordillera and Altiplano regions (Fig. 3). During this interval, the present site of the Subandean fold-thrust belt and foreland basin was a broad, shallow foreland basin. The low accumulation rate in the Subandean zone between 25 and 10 Ma (Fig. 2) implies only minor flexural loading of the Brazilian Shield by the internally deforming Eastern Cordillera. Subsidence within the Altiplano basin at this time may have been associated with west-vergent backthrusting of the Eastern Cordillera (Baby et al., 1990).

During the second stage (post–10 Ma), the upper crust of the Eastern Cordillera overthrust the Brazilian Shield on a mid-crustal detachment that is inferred to be the westward continuation of the Subandean master décollement (Fig. 3). We estimate a minimum shortening across the Subandean fold-thrust belt of 80–100 km; this amount corroborates other published studies (e.g., Baby et al., 1992; Hérail et al., 1990; Baby et al., 1989; Allmendinger et al., 1983). Preservation of structural balance requires that this shortening be balanced by underthrusting of the Brazilian Shield; this is supported by gravity studies (Lyon-Caen et al., 1985). A mid-crustal detachment is supported by seismic refraction data from ~22°S that indicate a velocity anomaly at this depth (Wigger et al., 1993). The crust below this detachment within the Eastern Cordillera and Altiplano is presumed to have deformed in a ductile manner, with the underthrust Brazilian Shield serving as the "hydraulic ram" (Isacks, 1985; Zhao and Morgan, 1985) that drove distributed shortening of the lower crust (Fig. 3).

As it was transported relatively eastward, the Eastern Cordillera served as the buttress or "bulldozer" (e.g., Dahlen and Suppe, 1988) that drove Subandean fold-thrust deformation by shearing the Phanerozoic sedimentary section off the underthrusting Brazilian Shield. During this interval, flexural subsidence within the foreland accelerated, and, in rapid succession, the newly deposited foreland strata were deformed and incorporated within the advancing fold-thrust belt. We hypothesize that acceleration of thrusting along the eastern margin of the Eastern Cordillera during this period led to a reduction in stream gradients that resulted in local aggradation on the evolving San Juan del Oro surface.

Assuming that the crust is compensated by Airy isostasy, the amount of isostatic uplift predicted by phase 1 shortening of 120–250 km is ~1.5–2.5 km. Accommodating this minimum of 100 km of additional crustal mass underthrust during phase 2 requires that the plateau did not reach its present height (3.7 km) prior to 10 Ma. Therefore, Subandean deformation probably began while the plateau was at an intermediate elevation, rather than at its present height. This deformation is more complex than that predicted by simple potential-energy calculations (Molnar and Lyon-Caen, 1988). We believe that this complexity is caused by the combined effects of (1) a preexisting subduction geometry that predetermined the plateau width by the heating and weakening of a swath of lithosphere and (2) structural heterogeneities within the crust which formed during earlier (Mesozoic and Paleozoic) deformations west of the Principal Frontal thrust and which are demonstrated by the pre-Cretaceous subcrop pattern.

The relatively abrupt eastward shift in the locus of upper-crustal deformation at 10 Ma could possibly have been driven by the crossing of an intrinsic threshold of lithospheric strength: at that point it simply involved less work to underthrust the Brazilian shield than to further shorten the upper crust of the Eastern Cordillera and Altiplano. Alternatively, an increased rate of convergence between the Nazca and South American plates in the late Miocene is a possible extrinsic cause for this change (Isacks, 1988).

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