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Late Oligocene–early Miocene major tectonic crisis and related basins in Bolivia

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ABSTRACT

Recent advances in biochronology, geochronology, magnetostratigraphy, structural geology, and basin analysis make untenable the traditional correlation of the first major Andean-age deformational episode in Bolivia with the middle Eocene "Incaic tectonic phase" defined in central Peru and instead demonstrate that the episode took place in late Oligocene and early Miocene time. This major tectonic crisis resulted in contemporary development of the Subandean external foreland basin and Altiplano intermontane basin, which were separated by the initiation of thrusting in the present Cordillera Oriental area. The deformation suggests that the Bolivian orocline began to develop at that time. It is likely that this tectonic upheaval is genetically linked to the marked increase in rate of plate convergence produced by the contemporaneous breakup of the Farallon plate.

INTRODUCTION

The onset of the main Andean orogeny in Bolivia has been traditionally attributed to the "Incaic tectonic phase," first dated as middle Eocene age in central Peru (Mégard, 1978; Noble et al., 1979). This widely accepted generalization of the "Incaic" deformation to cordilleran southern Peru and Bolivia (e.g., Martinez, 1980; Lavenu and Marocco, 1984) was based chiefly on paleontology, scarce geochronological data, and the assumption by most authors that central Andean compressive deformation was characterized by synchronous, short-lived tectonic pulses interrupting long, extension-dominated periods (e.g., Mégard et al., 1984).

However, progress in several avenues of research now requires a complete reconsideration of the whole question. First, the presumed Incaic deformation is postdated in Bolivia by fossiliferous clastic beds assigned to the South American land-mammal Deseadan stage: although long believed to be of early Oligocene age, recent progress in South American paleontology has shown that the Deseadan is middle Oligocene–earliest Miocene (Marshall, 1985; MacFadden et al., 1985). Second, new geochronological data show that the ages of some key stratigraphic units of the Altiplano are much younger than previously assumed (Swanson et al., 1987). Third, the tectonic models concerning the Peru-Bolivia Andes are being reevaluated. Whereas older interpretations envisioned that the Cenozoic Andes evolved in a regime characterized by long tensional periods governing basin developments, short synchronous compressional pulses, and generally high-angle faulting (e.g., Martinez, 1980; Sébrier et al., 1988), new data and new interpretations favor structural models dominated by crustal shortening, thrust propagation, and foreland-basin evolution (Jordan et al., 1983; Jordan and Alonso, 1987; Isacks, 1988; Roeder, 1988; Sempere et al., 1988, 1989).

The purpose of this paper is to summarize and clarify these recent structural and chronological data, some of them unpublished, and to demonstrate that a tectonic upheaval started in Bolivia in the late Oligocene and lasted ~8 m.y. Special attention is given to the tight genetic relations between this crustal-scale deformation, the contemporaneous development of the Altiplano and Subandean basins, and the inception of the Bolivian orocline. The tectonic regime that reigned in the central Andean area during the Cenozoic may therefore be reconsidered in this new light.

GENERAL SETTING

The area of interest (Fig. 1) comprises parts of the Altiplano, Cordillera Oriental, Subandean belt, and Llanura (lowlands) of Bolivia. However, these traditional morphologic units should no longer be used as structural provinces; the discussion hereafter is organized around four

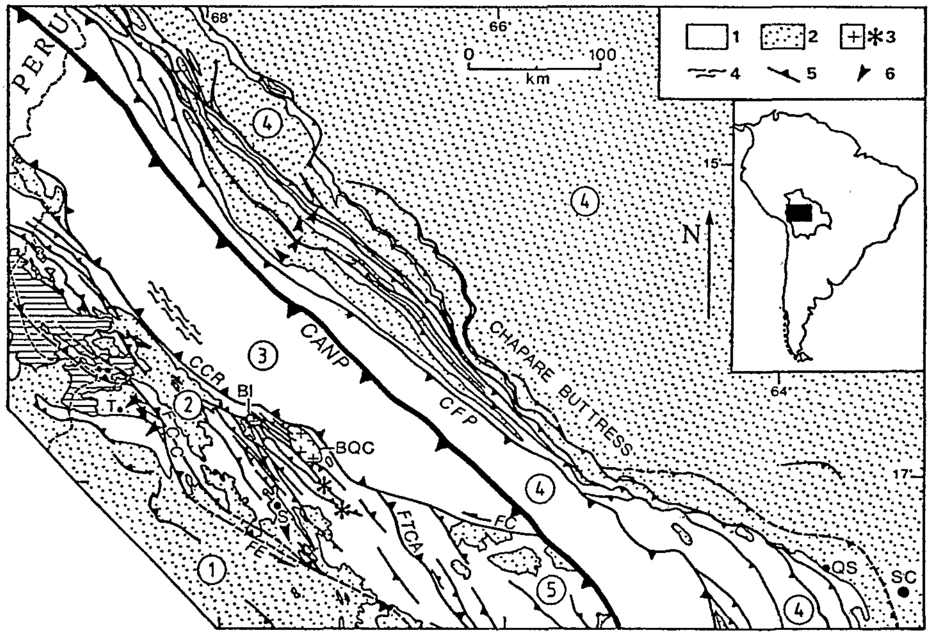

Figure 1. Simplified geologic map of northwestern Bolivia (after Pareja and Ballón, 1978; Martinez, 1980). Patterns and symbols: 1 = rocks of middle Oligocene and older age; 2 = sedimentary and volcanic rocks of late Oligocene and younger age; 3 = late Oligocene–early Miocene intrusions; 4 = Zongo tectonothermal domain of McBride et al. (1987); 5 = thrust faults; 6 = paleocurrents for upper Oligocene–lower Miocene strata. BI = Illimani batholith; BQC = Quimsa Cruz batholith; asterisks = small intrusions. Tectonostratigraphic domains (circled numbers): 1 = Altiplano; 2 = Huarina fold-thrust belt; 3 = Cordillera Real; 4 = Tarija-Teoponte and Subandean fold-thrust belts, and Llanura lowlands; 5 = Río Caine unit. Boundary faults (abbreviations for Spanish names): CANP = Main Andean thrust; CCR = Cordillera Real thrust; CFP = Main Frontal thrust; FC = Cochabamba fault; FCC = Coniri thrust; FE = Eucaliptus fault; FTCA = Arque thrust–Toracari fault. Localities: QS = Quebrada Saguayo, S = Salla, SC = Santa Cruz, T = Tiahuanacu. For more clarity, faults within domain 3 and late Miocene Tipuani basin (see Fornari et al., 1987) have been omitted.

fault-bounded tectonostratigraphic domains first defined by Sempere et al. (1988): from southwest to northeast, they are (1) the Altiplano, (2) the southwest-verging Huarina fold-thrust belt, (3) the Cordillera Real, and (4) the northeast-verging Tarija-Teoponte and Subandean belts and the Llanura (Fig. 1). The main structural boundary in Bolivia is the Cabalgamiento Andino Principal (i.e., Main Andean thrust; Sempere et al., 1988); it separates two distinct groups of tectonostratigraphic domains. In map view (Fig. 2), the boundary appears to be tightly linked to the Bolivian orocline (see Isacks, 1988). Figure 3A gives a synoptic view of most of the stratigraphic and isotopic data used to constrain the epoch of first major Andean deformation in the study area.

ALTIPLANO

In the northern Altiplano, the onset of the Andean deformation is recorded by a disconformity separating the older Tiahuanacu Formation from the younger Coniri Formation. The Tiahuanacu is slightly scoured beneath the gravels of the basal Coniri. The geometries and source areas of the respective basins, deduced from the paleocurrent data, are markedly different (Fig. 3A). The Tiahuanacu forms a 2500-m-thick red-bed sequence that coarsens and thickens upward; the sequence was deposited in a large foreland basin of Eocene to middle Oligocene age in domains 1, 2, 5, and possibly 3.

In addition to the chronological data displayed in Figure 3A, sanidine from a tuff from a southern unit equivalent to the middle Coniri yielded an age of 24.5 ±0.6 Ma (Swanson et al., 1987). The ages roughly bracket the Tiahuanacu-Coniri disconformity to between 25.5 and 29 Ma.

The strong paleocurrent change across the Tiahuanacu-Coniri contact and the coarseness and thickness of the Coniri imply a deep modification of paleogeography and sedimentary dynamics, due to the onset of deformation in a northeastern area; progressive unconformities are observed in Coniri strata close to the Coniri thrust, which in the field dips ~N45°E. Therefore, the nearby southwest-verging Huarina fold-thrust belt (domain 2) is believed to be part of the coevally deformed area. This geometry of deformation and deposition strongly suggests that the northern Altiplano functioned as a foreland basin during deformation in the Huarina fold-thrust belt. It is very likely that deformation progressed during deposition of most of the Coniri Formation, starting between 25.5 and 29 Ma. On the basis of the gradual transition from the Coniri to the Kollukollu Formation at 17–18 Ma (Fig. 3A), we believe that deformation near the Coniri thrust decreased considerably at ~19 Ma.

HUARINA FOLD-THRUST BELT

The Coniri thrust is the southwestern boundary of the Huarina fold-thrust belt (Fig. 1). In this domain, units that contain Deseadan mammals and that are partly equivalent to the Coniri Formation overlie deformed Eocene and older rocks in sharp and frequently angular unconformity (Martinez, 1980). These relations and the presumed age of the Deseadan have been a key factor in traditional interpretations of Incaic-age deformation in Bolivia.

The Salla fossiliferous beds transitionally overlie the Luribay conglomerate, which postdates the deformation. The Salla-Luribay series represents the longitudinal, northwest-onlapping

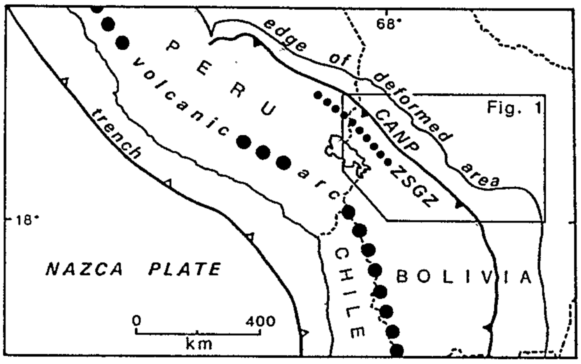

Figure 2. Structural sketch map of Bolivian orocline area. ZSGZ = Zongo-San Gabán tectonothermal zone of Farrar et al. (1988). CANP = Main Andean thrust.

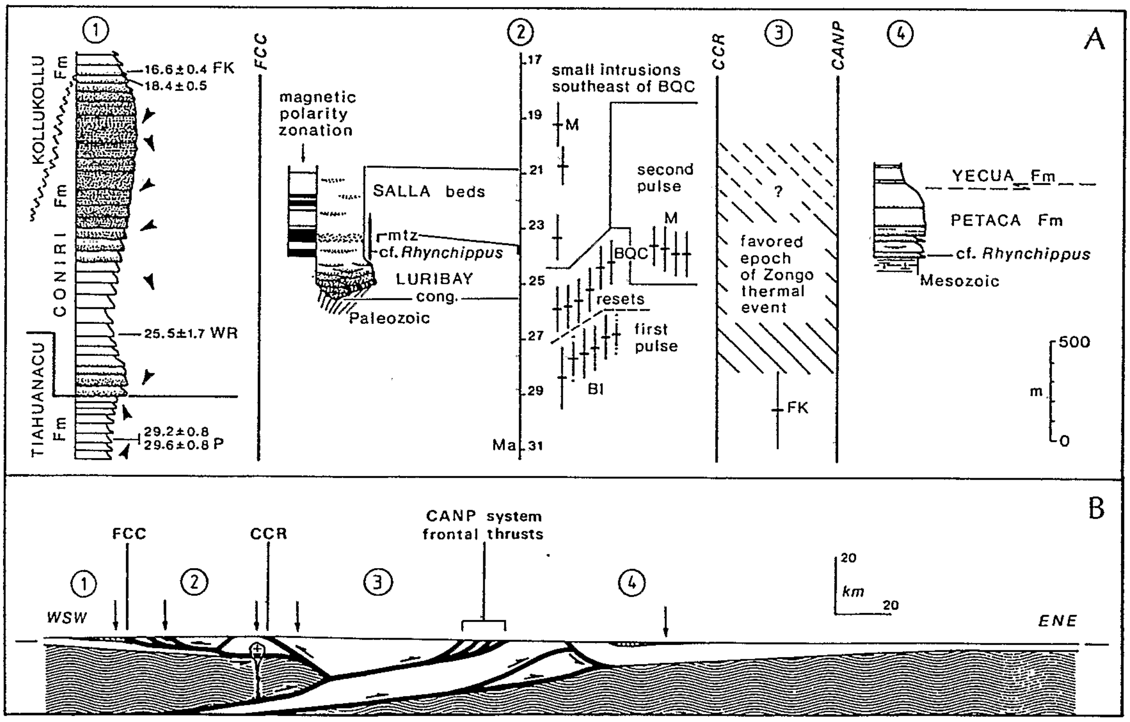

Figure 3. A: Synopsis of main data discussed in text. All ages are K-Ar. Material dated is biotite unless otherwise stated (FK = K-feldspar, M = muscovite, P = plagioclase, WR = whole rock). 1 = Composite schematic section; all ages are from Swanson et al. (1987), except new age documented in Table 1; arrows are azimuths of mean paleocurrents. 2 = Data for Salla beds slightly modified after MacFadden et al. (1985); mtz = main tuffaceous zone; favored correlation is explained in Figure 4 and in text; ages of intrusions from McBride et al. (1983), except two from R. Robertson (1974, unpublished) in Illimani batholith. 3 = New age documented in Table 1. 4 = Section by Sanjinés and Jiménez (1976). Abbreviations: same as in Figure 1. B: Schematic cross section illustrating functioning of Main Andean thrust (CANP) system and synchronous development of Subandean and Altiplano foreland basins at ~20 Ma. Legend: same as in Figure 1. Wavy-pattern areas: pre-Ordovician rocks. Vertical arrows show location of data displayed above.

alluvial fill of a piggyback basin cut into the deformed substratum and drained toward the eastern Altiplano (Fig. 1). The unit includes a main tuffaceous zone that comprises the 30 m interval just below the main fossiliferous level (Figs. 3A and 4).

A magnetostratigraphic study was performed on the Salla beds by MacFadden et al. (1985). These authors correlated their magnetic polarity zonation to the standard magnetic polarity scale by using a 26.4 Ma K-Ar age as a tie point (hypothesis 1). However, the magnetic pattern for this correlation appears partly unsatisfactory and does not agree with the fission-track data. An alternative correlation (hypothesis 2) can be made by using the fission-track ages as tie points and ignoring the 26.4 Ma age; this hypothesis suggests that the Salla beds are 3 to 4.5 m.y. younger than the age favored by MacFadden et al. (1985; Fig. 4).

Both hypotheses show some misfits with the standard magnetic polarity scale. However, in hypothesis 2, the main tuffaceous zone covers the interval from 23.6 to 23.9 Ma, closely coinciding with an important pulse of shallow magma emplacement 50 km northeast of Salla (see below). In addition, work by McRae (1989) improves the Salla magnetic polarity data and also favors younger ages. On the basis of hypothesis 2, which we therefore favor, deposition of the Luribay conglomerate began at ~25.5 Ma and, of particular importance to us (see below), the part of the Salla beds that contains cf. *Rhynchippus* notohippids covers the 23–24.5 Ma time span.

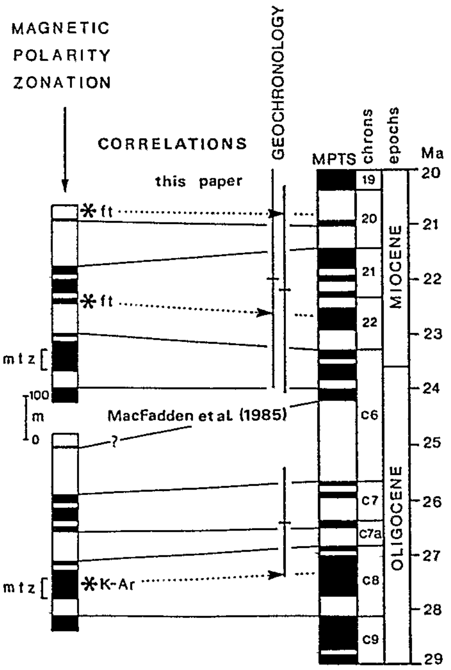

Figure 4. Possible correlations of Salla magnetic polarity zonation to standard magnetic polarity scale (MPTS; see Fig. 3A for stratigraphic section). All data are from MacFadden et al. (1985); ft = fission-track dates; mtz = main tuffaceous zone (see text).

The nonfoliated Quimsa Cruz and Illimani batholiths (Fig. 1) crop out northeast of the Salla area; they were studied and dated by McBride et al. (1983; Fig. 3A). These authors showed that granodioritic magma was emplaced at about 26.9–27.5 Ma in both areas and that a second pulse of granitic magma emplacement occurred in the Quimsa Cruz at about 23.6–23.9 Ma (the second pulse partially degassed radiogenic Ar from the earlier intrusions). Both magmatic units were probably emplaced at very shallow depths and display peraluminous characteristics that suggest crustal-fusion processes. The granitic pulse may correlate to the main tuffaceous zone of the Salla beds (see above).

Field relations show that the intrusions are postdated by southwest-verging thrusts. But, because of possible thrust reactivations, this does not preclude that thrusting began before or between the magma emplacements. Because these batholiths are the first plutons to have been emplaced in the study area since Triassic time, we believe that the chronological coincidence between this magmatism and the tectonism documented above is not fortuitous (Fig. 3A).

CORDILLERA REAL

Lower Paleozoic strata, as well as the Carboniferous Zongo granite and other Triassic plutons, crop out in this highly uplifted domain where thrusts are numerous. Very discordant K-Ar ages, combined with ^{40}Ar-^{39}Ar age spectra, on biotites, K-feldspars, and muscovites from the Zongo granite and associated metasedimentary rocks led McBride et al. (1987) and Farrar et al. (1988) to propose the existence in the Cordillera Real of a "structurally cryptic" tectonothermal event of late Eocene age, which they correlated with the Incaic phase.

Our own unpublished K-Ar data fully confirm age discordances in the Zongo granite; in addition, we obtained an age of 29.5 Ma (Table 1), younger than the youngest age (37.4 Ma) reported by McBride et al. (1987). Only one clear ^{40}Ar-^{39}Ar plateau, at 38.9 Ma, was obtained by McBride et al. (1987), but their sample CR 361 from the Zongo granite showed low-temperature step ages of ~25 Ma for nearly 20% of the Ar released. These data suggest that there is no good definition yet of the age of the thermal resettings that have affected the Cordillera Real, and that at least one was younger than 29.5 Ma and perhaps close to 25 Ma. In any case, the thermal event demonstrated by Farrar et al. (1988), which is younger than 38 Ma, cannot be directly related to the Incaic phase defined in central Peru, which is older than 41 Ma (Noble et al., 1979).

The simplest interpretation would be that the discordant ages originated during a single episode of crustal heating. We also favor the hypothesis that such an event occurred during late Oligocene–early Miocene time because the Zongo tectonothermal domain, the Illimani and Quimsa Cruz batholiths, and the small intrusions southeast of the latter define a rough alignment parallel to the Main Andean thrust (Fig. 1).

TARIJA-TEOPONTE AND SUBANDEAN BELTS, AND LLANURA

The first deposits of the Cenozoic Subandean basin, the Petaca and age-equivalent Bala formations, overlie Mesozoic sedimentary rocks with a sharp, slightly erosive, unconformity. Both units are composed of sandstones and subordinate mudstones and conglomerates and constitute the oldest part of the 4000- to 6500-m-thick clastic strata deposited in the last Andean foreland basin. At Quebrada Saguayo, the notohippid cf. *Rhynchippus* was found 2 m above the base of the Petaca. It was described by C. Villarroel as late Deseadan in age and is very similar to forms found at Salla (Sanjinés and Jiménez, 1976). This fossil should thus indicate a similar age, i.e., the latest Oligocene–earliest Miocene interval (see above). Its occurrence at the base of the Cenozoic series at Quebrada Saguayo allows us to place the onset of the Subandean foreland basin during late Oligocene time.

SUMMARY, DISCUSSION, AND CONCLUSIONS

The late Oligocene appears to have been the time of a considerable tectonic, sedimentary, and magmatic crisis in Bolivia, as conjectured by Pilger (1984). Because the Bolivian territory was east of the Andean deformation front during Eocene to middle Oligocene time (Sempere et al., 1989), this crisis can be described as a

TABLE 1. ANALYTICAL DATA, CONIRI FORMATION AND ZONGO GRANITE

	Sample number	K_2O* (%)	^{40}Ar rad / ^{40}Ar tot	^{40}Ar rad (nl/g)	Age (Ma ±2 σ)
Coniri tuff	86 MB 338	WR 0.832	21.68	0.689	25.5 ±1.7
Zongo granite	86 MB 304	FK 14.38	94.6	13.80	29.5 ±1.4

*WR= whole rock; FK= K-feldspar.

"jump" of the external Andean foreland basin from domains 1, 2, and 5, and possibly 3, to the present position in domain 4 (Fig. 1). Initiation of the Subandean foreland basin points to contemporary inception of the Main Andean thrust system: this emergence of deformation in domains 2 and 3 thus resulted in the splitting of the sedimentation area into the coeval Altiplano (intermontane) and Subandean (external) basins. Existing semibalanced cross sections (Roeder, 1988) show that the Cordillera Real thrust and the Huarina fold-thrust belt constitute a southwest-verging "backthrust belt" of the Main Andean thrust system (Fig. 3B), which generated its own foreland basin in the northern Altiplano during the time of deposition of the Coniri Formation. Late Oligocene inception of the Main Andean thrust system apparently also coincided with crustal fusion and possibly heating in domains 2 and 3; this finding suggests a crustal-scale character for the crisis.

The rate of the South American–Nazca (Farallon) plate convergence increased markedly at anomaly 7, i.e., at ~26 Ma (Pardo-Casas and Molnar, 1987; however, there remain uncertainties about the ages of the magnetic anomalies and about the accuracy of the interpolation method used in dating most of them: see Odin, 1989). Establishment of a volcanic arc in the western Andes at ~26–27 Ma has been related to the plate-motion change (Jordan and Alonso, 1987). The progressive breakup of the Farallon plate at ~26 Ma (Wortel and Cloetingh, 1981) was roughly synchronous with the onset of the crisis documented in Bolivia. Therefore both are probably genetically related.

Specifically, between lat 12° and 24°S, the late Oligocene South American Pacific margin reacted to new subduction-induced stresses by large-scale compressional failure. Because the Bolivian orocline is closely related to the Main Andean thrust (in map view; see Fig. 2), it is likely that the orocline bending also began in late Oligocene time (Sempere et al., 1989, and unpublished). The data and interpretations we have presented synoptically suggest that a first stage in the orocline development, involving deformation and magmatism, was progressively achieved between ~27 and ~19 Ma. Thus neither the age (late Oligocene–early Miocene) nor the duration (~8 m.y.) of this major crisis in the Bolivian orocline area is compatible with traditional notions of Andean tectonics.

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A very exciting and provocative contribution.
Rex H. Pilger

Challenges long-held tectonic interpretations.
Teresa E. Jordan
