The kinematic history of the central Andean fold-thrust belt, Bolivia: Implications for building a high plateau

Nadine McQuarrie*
Department of Geosciences, University of Arizona, Tucson, Arizona 85721, USA

ABSTRACT

This paper presents a model for the kinematic evolution of the central Andean plateau based on balanced cross sections across the Bolivian Andes. The proposed model links the formation of the Andean plateau to the development of the Andean fold-thrust belt through the creation and propagation of two large basement megathrusts. Support for large, basement-involved thrust sheets is found in significant steps in both the topography and the exposed structural elevation of the Andean fold-thrust belt. The structurally highest basement thrust raised folds and faults in predominantly lower Paleozoic rocks of the Eastern Cordillera with respect to Tertiary rocks in the broad, internally drained basin of the Altiplano to the west, and east-verging folds and faults in upper Paleozoic rocks of the Interandean zone to the east. The Interandean zone was in turn raised (both structurally and topographically) with respect to the frontal folds and faults of the fold-thrust belt (the Subandean zone) by a second, structurally lower basement thrust sheet. Thus, these two megathrusts divide the Andean fold-thrust belt into four areas of markedly different structural elevations. The Eastern Cordillera can be further subdivided into two zones of west- and east-vergent folds and thrusts.

Shortening accommodated by the fold-thrust belt can be divided among these tectono-structural zones and linked to shortening accommodated by the inferred basement megathrusts. The proposed kinematic model suggests that the eastward propagation of the structurally highest basement thrust fed ~105 km of slip into the Eastern Cordillera along east-vergent and west-vergent faults. This structure also fed ~90 km of eastward slip into the Interandean zone. The initiation and eastward propagation of a lower basement thrust structurally elevated the Interandean zone with respect to the foreland while feeding ~65 km of slip into the Subandean zone. Out-of-sequence basement thrusting to the west is proposed to have elevated the western edge of the plateau and accommodated ~40 km of shortening within the Altiplano. Total cumulative shortening within the cover rocks of the Andean fold-thrust belt (300–330 km) can be balanced by an equivalent amount of shortening along two basement megathrusts. To the first order, the eastern margin of the central Andean plateau (defined by the 3 km topographic contour) is contiguous with the leading edge of the upper basement megathrust. This relationship between the basement highs and the physiographic boundaries of the Andean plateau suggests that extensive megathrust sheets (involving strong rocks such as crystalline basement or quartzite) play an important role in the formation of the central Andean plateau, and a similar link between megathrust sheets and plateaus may be found in other orogens.

Keywords: Andes, Bolivia, fold-thrust belts, kinematics, plateaus.

INTRODUCTION

The processes involved in building a high-elevation plateau are still hotly debated, with many of the arguments centered around the relative importance of crustal underthrusting, magmatic additions, thermal effects, and distributed shortening (Dewey et al., 1988; Isacks, 1988; Harrison et al., 1992; Molnar et al., 1993; Wdowinski and Bock, 1994; Allmendinger et al., 1997, Matte et al., 1997). Perhaps because of the difference in the plate tectonic settings, geologic histories, and original boundary conditions of the Tibetan and Andean Plateaus, the general models of plateau formation are often simplified and present the orogens as compositionally and structurally homogeneous. Existing models emphasize many of the similarities between the Tibetan and Andean plateaus such as the concept of a gravitational lid (Molnar and Lyon-Caen, 1988; England and Houseman, 1989), weak lower crust (Royden, 1996), or wide zones of preexisting weaknesses (Isacks, 1988; Wdowinski and Bock, 1994). Important and unique features that are not integrated into these models, such as individual folds, faults, and sedimentary basins, may provide additional insight into the processes involved in plateau formation and emphasize the importance of heterogeneities in the growth and formation of plateaus (e.g., Lamb and Hoke, 1997; Yin et al., 1999).

The goal of this paper is to assess whether the growth of the central Andean plateau can be linked to the kinematic development of the fold-thrust belt by presenting regional balanced cross sections based on field traverses across the entire width of the Andean fold-thrust belt in Bolivia. Balanced cross sections from the arc to the foreland in conjunction with available timing constraints enable sequential restorations of the fold-thrust belt with time as well as provide realistic estimates of shortening. Cross sections through the Andean fold-thrust belt must satisfy three regional constraints. These are (1) a 12 km structural step between the Altiplano and the Eastern Cordillera (McQuarrie and DeCelles, 2001), (2) a horizontal, shallow level décollement in lower Paleozoic rocks through the west- and east-verging portions of the Eastern Cordillera (McQuarrie and DeCelles, 2001), and (3) pronounced (~6 km) structural steps between the Interandean zone and the Eastern Cordillera and between the Interandean zone and the Subandean zone (Kley et al., 1996; Kley, 1996, 1999). The cross sections and kinematic evolution models presented in this paper pro-

*Present address: Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125, USA; e-mail: nmcq@gps.caltech.edu.

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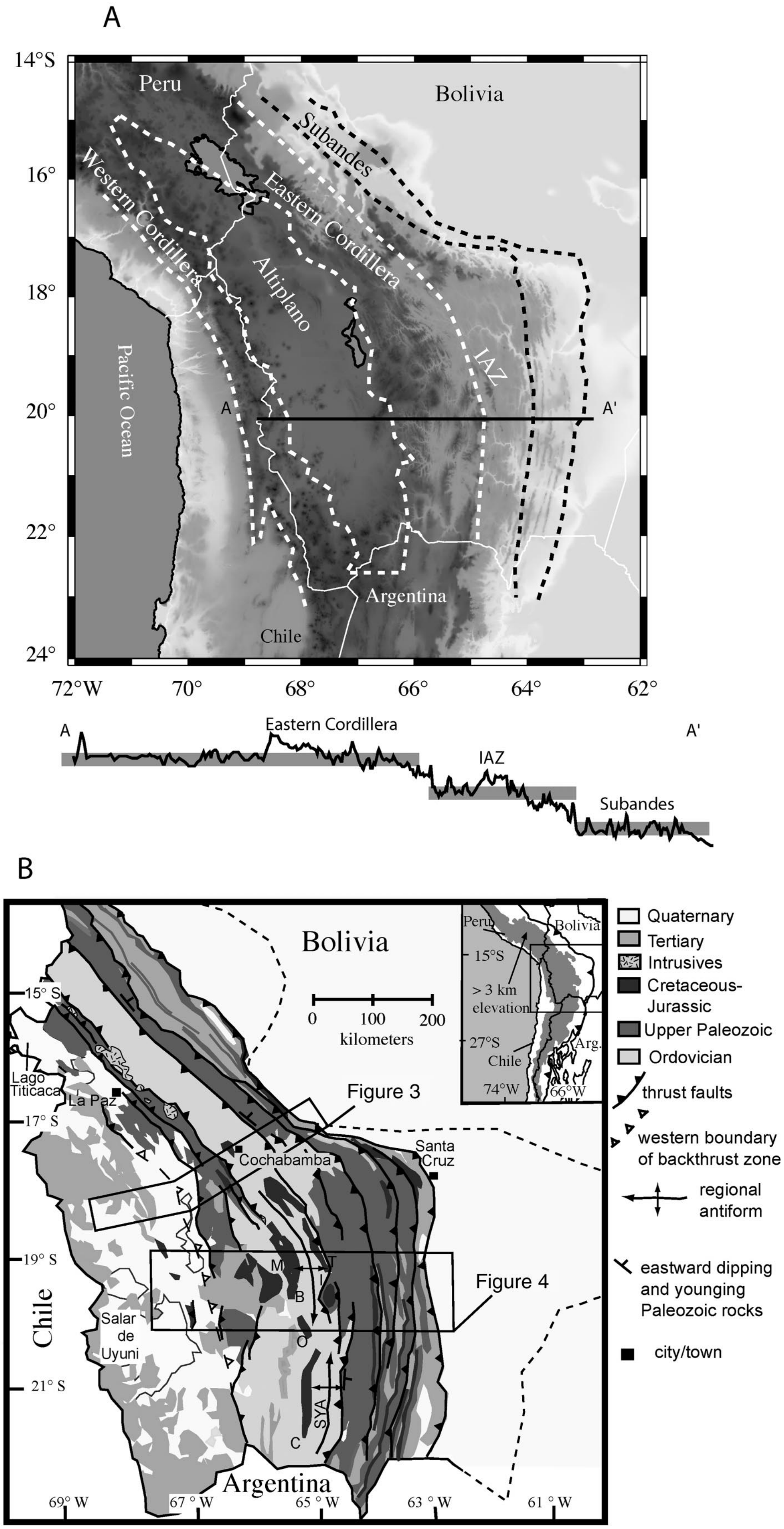

Figure 1. (A) Topography of the central Andes with major physiographic divisions separated by dashed lines and topographic profile highlighting topographic steps. Wide gray bands mark zones of average elevation. IAZ is the Interandean zone defined by Kley (1996). (B) Generalized geologic map of Bolivia (simplified from Pareja et al., 1978) illustrating major lithologic boundaries, thrust systems, and locations of cross sections. Boxes are locations of Figures 3 and 4; SYA—Sama-Yunchará anticlinorium, C—Camargo syncline, O—Otavi syncline, I—Incapampa syncline, B—Betanzos syncline, T—Tarabuco syncline, M—Maragua syncline. Inset (modified from Isacks [1988]) shows the geographical extent of the Andean plateau and the location of the central Andean portion of the plateau.

pose that the best way to meet these three constraints is through the stacking of two large basement thrust sheets. The eastern edge of the higher thrust sheet is contiguous with the eastern edge of the Andean plateau. This suggests that perhaps long (100–200 km), thin (15 km) basement megathrusts may have exerted the largest control on the physiographic boundaries of the Andean plateau, implying the growth history of the plateau cannot be understood outside the context of the kinematic history of the fold-thrust belt.

GEOLOGIC BACKGROUND

The central Andean plateau is defined as a broad area of internally drained basins and moderate relief with an average elevation of ≥3 km (Isacks, 1988) (Fig. 1). In Bolivia, the western edge of the plateau is the active volcanic arc of the Western Cordillera. The eastern edge is the folded and faulted hinterland of the Andean fold-thrust belt exposed in the high peaks of the Eastern Cordillera. Centered between the cordilleras is the internally drained basin of the Altiplano (Fig. 1). On the eastern side of the Andean plateau, the elevation decreases away from the plateau in a stepwise fashion. The first topographic step is from the 3 km edge of the plateau to the 2 km high Interandean zone. The eastern edge of the Interandean zone is another abrupt drop in elevation to the 1 km average elevation of the Subandean zone (Fig. 1).

The central Andean plateau is thought to be primarily the result of tectonic shortening and thickening associated with the Andean fold-thrust belt (Isacks, 1988; Roeder 1988; Sheffels, 1990; Gubbels et al., 1993; Schmitz, 1994; Wdowinski and Bock, 1994; Allmendinger et al., 1997; Baby et al., 1997; Jordon et al., 1997; Lamb and Hoke, 1997; Kley and Monaldi, 1998; Pope and Willett, 1998). Shortening estimates for the Bolivian Andes range from 210 to 336 km (Sheffels, 1990; Schmitz, 1994; Kley, 1996; Baby et al., 1997; Kley and Monaldi, 1998; McQuarrie and DeCelles, 2001) and can account for most if not all of the 70-km-thick crust (Beck et al., 1996) of the plateau in Bolivia. In the central Andes, the fold-thrust belt is bivergent. The axes of vergence in the upper crustal rocks is centered in the Eastern Cordillera (Roeder, 1988; Sempere et al., 1990; Roeder and Chamberlain, 1995; Baby et al., 1997; McQuarrie and DeCelles, 2001), with an extensive west-verging backthrust system extending from the high peaks of the Eastern Cordillera into the Altiplano to the west.

The cover rocks involved in the Andean fold-thrust belt are a thick (~15 km), continuous succession of Paleozoic marine siliciclastic rocks, a thinner, discontinuous section (2–4 km) of nonmarine Carboniferous through Cretaceous rocks (Roeder and Chamberlain, 1995; Sempere, 1994, 1995; González et al., 1996), and locally thick sections (up to 12 km within the Altiplano) of Tertiary synorogenic sedimentary rocks (Sempere et al., 1990; Kennan et al., 1995; Lamb and Hoke, 1997) (Fig. 2). The thickest part (~15 km) of the Paleozoic succession is centered in the Eastern Cordillera (Sempere, 1995; Roeder and Chamberlain, 1995; Welsink et al., 1995) and tapers eastward onto the Brazilian shield (Welsink et al., 1995) and westward toward the Altiplano (Sempere, 1995; Roeder and Chamberlain, 1995).

The importance of basement involvement in the Andean fold-thrust belt has been discussed by several authors (Wigger et al., 1994; Dunn et al., 1995; Kley, 1996, 1999; Kley et al., 1996; Baby et al., 1997, Schmitz and Kley, 1997; Allmendinger and Zapata, 2000; McQuarrie and DeCelles, 2001), although the geometry of the interpreted basement structures varies. McQuarrie and DeCelles (2001) proposed that the 100-km-long west-verging backthrust belt within the Eastern Cordillera, in conjunction with a 12 km structural step between the backthrust belt and the Altiplano basin, is best explained through the eastward propagation of a basement thrust sheet over a 12 km ramp. Elevated basement at the eastern edge of the Andean Plateau as suggested by gravimetric and magnetotelluric data (Kley et al., 1996; Schmitz and Kley, 1997; Kley, 1999) was proposed to be the eastward continuation of this basement thrust sheet. Although this basement thrust sheet accounted for the structural steps within the fold-thrust belt, the kinematics that linked the basement deformation to the cover deformation was not addressed. This paper extends the cross sections of McQuarrie and DeCelles (2001) eastward to the foreland to evaluate the importance of basement deformation in the central Andean fold-thrust belt, but also to evaluate which geometries of basement deformation are most compatible with kinematically restorable cross sections through time.

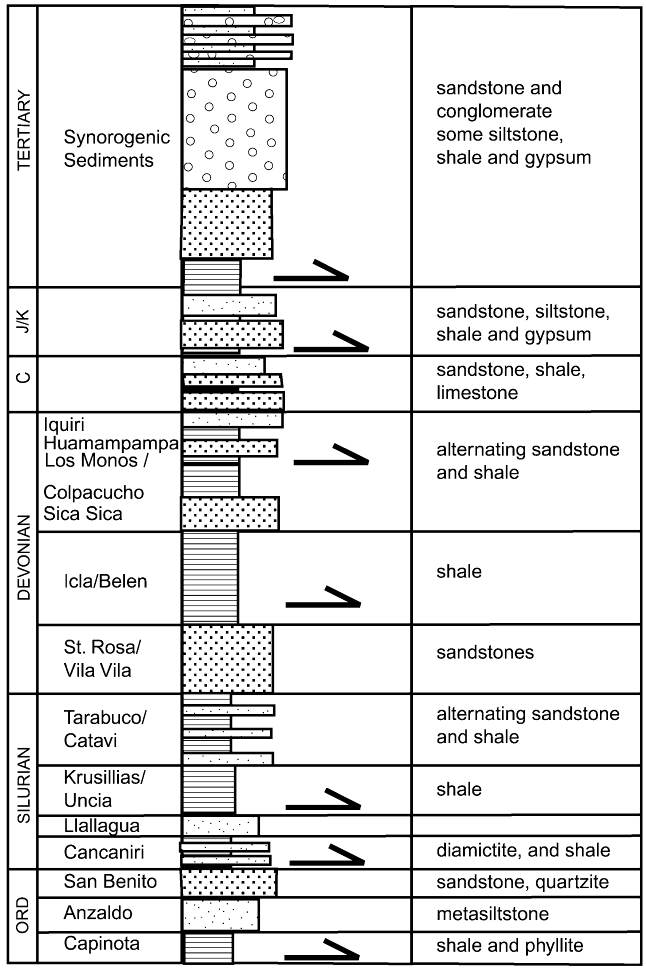

Figure 2. Simplified stratigraphic column for the central Andean fold-thrust belt from Roeder and Chamberlain (1995), Sempere (1995), Dunn et al. (1995), González et al. (1996), and Lamb and Hoke (1997). Dark arrows indicate major detachment horizons. Formations that change names from the east to the west side of the orogen are separated by a slash.

BALANCED CROSS SECTIONS

This work builds upon a decade of structural studies across the central Andean fold-thrust belt and incorporates balanced cross sections that exist for the frontal portions of the Andean fold-thrust belt (Roeder, 1988; Herail et al., 1990; Dunn et al., 1995; Roeder and Chamberlain, 1995; Kley, 1996) and those that extend into the hinterland (Sheffels, 1988; Lamb and Hoke, 1997; Baby et al. 1997; Kley et al., 1997; Rochat et al., 1999), in a way that allows for sequential reconstruction of the fold-thrust belt as a whole.

Methods

Balanced cross sections were constructed along two transects across the Andean fold-thrust belt from the undeformed foreland to the volcanic arc. The northern transect (lat 17°–18°S) extends west-northwest across the fold-thrust belt with a cross-strike distance of ~440 km. The southern transect (19°–20°S) is an east-west transect with a cross-strike distance of ~550 km (Fig. 1). Because roads through the central Andes do not follow the same latitude, the cross sections have 1 to 3 breaks in each section, permitting the cross section to follow the mapped geology. The breaks in the section correspond to significant along-strike structures, allowing the cross section to be accurately projected north or south (Figs. 3 and 4)[1]. The interpretations presented in the balanced cross sections are based on new mapping at a scale of 1:50 000 along each transect. The new mapping was compiled on to 1:250 000-scale topographic maps in conjunction with existing (1:100 000 and 1:250 000) geologic maps to construct the cross sections. Reflection seismic sections and well data (courtesy of Yacimientos Petroleros Fiscales Bolivianos [YPFB]) aided in the interpretation of structures beneath the Altiplano and the southern Subandean zone (YPFB proprietary data; Dunn et al., 1995).

The cross sections were balanced using the sinuous bed method (Dahlstrom, 1969). This involves measuring the lengths of the top and bottom of each formation between faults and matching ramp and flat lengths on the restored section with those on the deformed section while maintaining bed thickness. Area balance was used to account for thickening of hinge zones and thinning of limbs as documented from structures in the field. The reasoning and the justification behind detailed aspects of each cross section are annotated on the balanced cross sections (Figs. 3 and 4). The balanced cross sections and the accompanying undeformed sections were simulated using the computer program, 2D-MOVE (Midland Valley) to produce sequentially restored sections that portray how the fold-thrust belt may have evolved through time.

Designation of Zones

The discussion of the balanced cross sections across the Andean fold-thrust belt is divided into tectono-structural zones based on the relationship between packages of structures with similar vergence, offsets, geometries, and structural level. These zones are as follows: Subandean, Interandean, Eastern Cordillera, and Altiplano. In this paper, the Eastern Cordillera zone is further subdivided into a western section of generally west-verging faults (the Eastern Cordillera backthrust zone) and an eastern section of east-verging faults (the Eastern Cordillera forethrust zone). The segments will be discussed from east to west in the direction of increasing structural complexity and decreasing subsurface data.

[1]Figures 3 and 4 are on a separate sheet accompanying this issue.

Foreland

The foreland basin geometry is known from numerous seismic lines and well data. The proximal depth of foredeep sediments in the northern cross section is 5 km with a basement slope of 4° toward the fold-thrust belt (Fig. 3) (Baby et al., 1995; Roeder and Chamberlain, 1995; Welsink et al., 1995). The foreland basin to the south is shallower, 3 km deep, and the dip of the basement is less pronounced, 2° toward the mountain belt (Fig. 4) (Baby et al., 1992; Dunn et al., 1995).

Subandean Zone

The Subandean zone along the northern transect (Fig. 3) consists of faulted folds within Tertiary foreland basin sedimentary rocks, a narrow zone of thrusts in Cambrian through Devonian rocks, and a thrust sheet of Cambrian through Silurian rocks. The geometry of the Cambrian through Silurian thrust sheet can be seen readily on geologic maps (Figs. 1 and 3). The panel of rock is essentially horizontal with respect to the line of the cross section but is dipping homogeneously to the northwest at ~35° (Fig. 3, #7). In this area of the cross section and directly south are some of the few places where Cambrian rocks involved in the fold-thrust belt are exposed at the surface (Fig. 3) (Pareja et al., 1978; Suarez et al., 2001), suggesting the presence of basement in the shallow subsurface. This structural high extends ~50 km to the southeast (Figs. 1 and 3) such that the regional exposure of the older rocks most likely reflects lateral footwall ramps that raise this basement high. Northeast of this wide strip of Cambrian rocks is a narrow fault-bounded syncline also in Cambrian rocks. Due to its limited east-west extent, and the stratigraphic separation on the faults, this fault-bounded syncline is interpreted to be a klippe of the Cambrian through the Devonian thrust sheet (Fig. 3). The narrow zone of faulted Ordovician through Devonian rocks between the outcrop exposures of Cambrian is interpreted to be two subsidiary horses, which fed slip into the Cambrian thrust sheet (Fig. 3, #3). The elevated level of basement (Fig. 3, #5) can be accounted for by the presence of a major basement thrust suggesting that the shortening within the Subandean zone is accommodated by motion along this thrust.

The geometry of the southern Subandean zone has been well documented (especially close to the foreland), and images of the predominant structures have been identified on numerous seismic lines (Baby et al., 1992; Dunn et al., 1995). The map pattern is one of narrow anticlines, often broken by thrust faults, and separated by broad synclines (Fig. 4). Resistant Carboniferous sandstone holds up the anticlinal ridges that create the distinctive valley and ridge topography (Fig. 1). Based on seismic and cross-sectional interpretation, two predominant geometries of folds and faults are present in the Subandean zone. Fault-bend folds form in Silurian to Lower Devonian rocks and tight fault-propagation folds dominate the near-surface structure. Tight anticlines are a result of westward wedging and internally deforming Upper Devonian shale. This wedging is visible in three seismic lines that cross the Charagua anticline (Dunn et al., 1995) and are supported by well data along other anticlinal structures (such as the Sararenda anticline, Fig. 4) (Baby et al., 1992; Dunn et al., 1995). Typically the anticlines are breached by breakthrough thrusts that nucleate in the overtightened back limb of a fault propagation anticline (Fig. 4) (Dunn et al., 1995). The southern Subandean zone is interpreted to be an in-sequence, thin-skinned thrust system detached along Lower Silurian shale (Fig. 4) (Dunn et al., 1995).

Interandean Zone

Throughout the Interandean zone in the northern study area, the structural style at the surface is repeating sections of Upper Ordovician rocks and Lower Silurian shale (Fig. 3). Bedding generally dips at a low angle, 20°–40°W, and the relationship of hanging-wall to footwall bedding suggests that most of these faults where seen at the surface are hanging-wall flat on footwall flat. The cross-sectional interpretation of this map pattern is long bed lengths of the mechanically strong Upper Ordovician and Silurian formations balanced by a series of horses in the weak Lower Ordovician shale (Fig. 3, #9). The western boundary of the Interandean zone in the northern cross section is the Cochabamba normal fault (Fig. 3). The Cochabamba fault has been interpreted to be a shallow normal fault associated with left-lateral slip within the Eastern Cordillera (Sheffels, 1995; Kennan et al., 1995). The cross-sectional interpretation presented in this paper suggests that the fault is minor (with Normal fault offsets of ~2.5 km) and that it is a ‘‘thin skinned’’ feature of the fold-thrust belt, detaching in Lower Ordovician shale (Capinota Formation) as suggested by Sheffels (1995).

Although the structures are more tightly deformed and accommodated at a different structural level, the general geometry of the Interandean zone in the southern cross section is similar to the Subandean zone. The lower horses are interpreted to detach at the base of the Ordovician and involve Ordovician through Lower Devonian to the east and, as the Ordovician thickens, only Ordovician to the west. In the western part of the Interandean zone, imbricated, long bed-length thrusts within the Ordovician are proposed to bring the older rocks near the surface (Fig. 4).

Eastern Cordillera Forethrust Zone

The Eastern Cordillera forethrust zone is typically a belt of thin-skinned, east-verging thrust faults that are structurally elevated, with respect to the Interandean zone (Figs. 3 and 4). In the northern section, the forethrust zone contains only the slightly deformed undulating Ordovician surface east of the Cochabamba normal fault (Fig. 3). This structurally elevated area of minimal deformation argues for basement close to the surface.

The structure of this zone in the southern cross section is a broad regional anticlinorium bounded to the west and east by regional synclines. Second-order faults and folds within the cover rocks complicate the general antiformal structure. The predominant style and geometry of structures in the zone are similar to those of the Interandean zone. However, in the forethrust zone the fault-bend horses are in the Lower Ordovician rocks, and the regional detachment horizon for the fault propagation folds is just below the stronger Upper Ordovician quartzite.

Eastern Cordillera Backthrust Zone

The backthrust zone is a belt of westward-verging and westward-propagating thrust faults that extend from the high peaks of the Eastern Cordillera westward into the Altiplano (Roeder, 1988; Sheffels, 1988; Sempere, 1990; Baby et al., 1990, 1997; Roeder and Chamberlain, 1995; McQuarrie and DeCelles, 2001). This zone is dominated by tight folds (wavelengths of 5–10 km) and steep (45°–65°), generally eastward-dipping thrust faults with 5–40 km of displacement (Figs. 3 and 4). The faults throughout the Eastern Cordillera backthrust zone often breach the shared limbs of folds placing hanging-wall anticlines over footwall synclines. The axes of many of the synclines have cores of Jurassic strata. The common regional elevation of many of the Jurassic-cored synclines suggests a relatively shallow and uniform detachment horizon. In order to keep a relatively shallow and uniform detachment horizon, and because the oldest rocks exposed in the Eastern Cordillera backthrust zone are in the Ordovician Anzaldo Formation, the main detachment level for the backthrust zone is proposed to be within the Lower Ordovician shale. Evidence for westward propagation of the backthrust zone is found in duplexes in the eastern parts of the zone, which require that the thrusts broke in sequence from east to west (Boyer and Elliott, 1982) and from older units and deeper exposures in the east than the west (McQuarrie and DeCelles, 2001). Apatite fission track ages that are oldest at the apex of the west and east-verging parts of the Eastern Cordillera zone and young to the west and east (respectively) (Ege et al., 2001) also argue for faults younging in the direction of vergence.

Altiplano Zone

The transition between the backthrust zone and the Altiplano is one in which the west-verging backthrust belt places Silurian rocks against Tertiary synorogenic sedimentary rocks (Figs. 3 and 4). The dominant structure within the Altiplano is a large, 10+ km amplitude syncline in Tertiary rocks. In the northern cross section, this structure is the Corque syncline. The amplitude of the Corque syncline is supported by both map data (Geobol, 1995b; Kennan et al., 1995; Lamb and Hoke, 1997; McQuarrie and DeCelles, 2001) and seismic reflection data (Lamb and Hoke, 1997). The structure of the transition zone between the Eastern Cordillera and the Altiplano can be seen on industry seismic lines from approximately the same area as shown in the northern cross section (see McQuarrie and DeCelles [2001] for details on the seismic data). Seismic lines and associated well data indicate that under the Lago Poopo basin, ~5 km of young (<25 Ma) synorogenic sedimentary rocks rest directly on Silurian strata (Fig. 3). This suggests that Devonian through Paleocene (and possibly through Oligocene) rocks were removed before ca. 25 Ma. Seismic data also suggest that the level of the Paleozoic section under the Lago Poopo basin is intermediate between its level in the backthrust zone and its level beneath the Corque syncline directly to the west.

Basement rocks exposed at the surface in the western Altiplano suggest the basement was uplifted ~12 km with respect to the base of the Corque syncline (Fig. 4). The growth of this basement high is manifested by Tertiary growth structures seen on seismic lines west of the Corque syncline along the same line of section as the northern cross section. These growth structures diverge eastward, suggesting that the basement was uplifted with respect to the syncline between 25 and 5 Ma (McQuarrie and DeCelles, 2001). The crustal duplex in the hinterland of the northern section is inferred to fill this space and lift basement with respect to the Corque syncline (Fig. 3). The slip accommodation by faulting on both the western and eastern limbs of the Corque syncline is ~40 km, much more than can be accounted for by simple out of the syncline slip. The slip is the minimal amount necessary to move hanging-wall cutoffs and erosional truncations through the erosion surface.

The Altiplano zone at the latitude of the southern cross section is deformed in an east-verging fold belt termed the Rio Mulato fold belt (McQuarrie and DeCelles, 2001). The fold belt is a series of large-amplitude (up to 8 km), salt-cored folds in Cretaceous and younger rocks, which detach in Jurassic/Cretaceous salt. Many of the folds are broken by minor thrust faults that verge eastward (McQuarrie and DeCelles, 2001) (Fig. 4). The Rio Mulato fold belt is thrust over Miocene sedimentary rocks of the Quehua Formation on an east-verging fault that is interpreted to be the basal detachment for the fold belt (Fig. 4). The structures shown west of the Salar de Uyuni are inferred from seismic lines and well data in the area of Salinas de Garcia Mendoza (Fig. 4). The seismic lines show a large-amplitude syncline of the same order of magnitude as the Corque syncline to the north. The seismic lines also reveal the gentle eastward dip and possible growth in the synorogenic sedimentary rocks west of the salt-cored, fault-propagation fold beneath the Salinas de Garcia Mendoza well. These gentle eastward dips may reflect the same growth of the basement duplex as proposed for the western growth structures seen on the seismic lines to the north (McQuarrie and DeCelles, 2001).

Basement Geometry

The abrupt increase in structural elevation between the Subandean, Interandean, and Eastern Cordillera zones imparts a regional geometry to the Andean fold-thrust belt that must be accounted for structurally. Changes in structural elevation within a fold-thrust belt do not reflect simple changes in décollement horizons; it is, rather, an effect of raising material as rocks are lifted up and over hanging-wall and footwall ramps. These ramps can be in sedimentary rocks (creating a doubling of the sedimentary thickness) or in basement rocks. Figure 5 shows the deformed sedimentary cover shell across southern Bolivia (compare with Fig. 4) with four possible deformation styles. Figure 5A indicates the area that would need to be filled through the doubling of sedimentary strata, and Figure 5, B–D, illustrates possible basement deformation geometries. The arguments for basement involvement in each of the structural zones are given below.

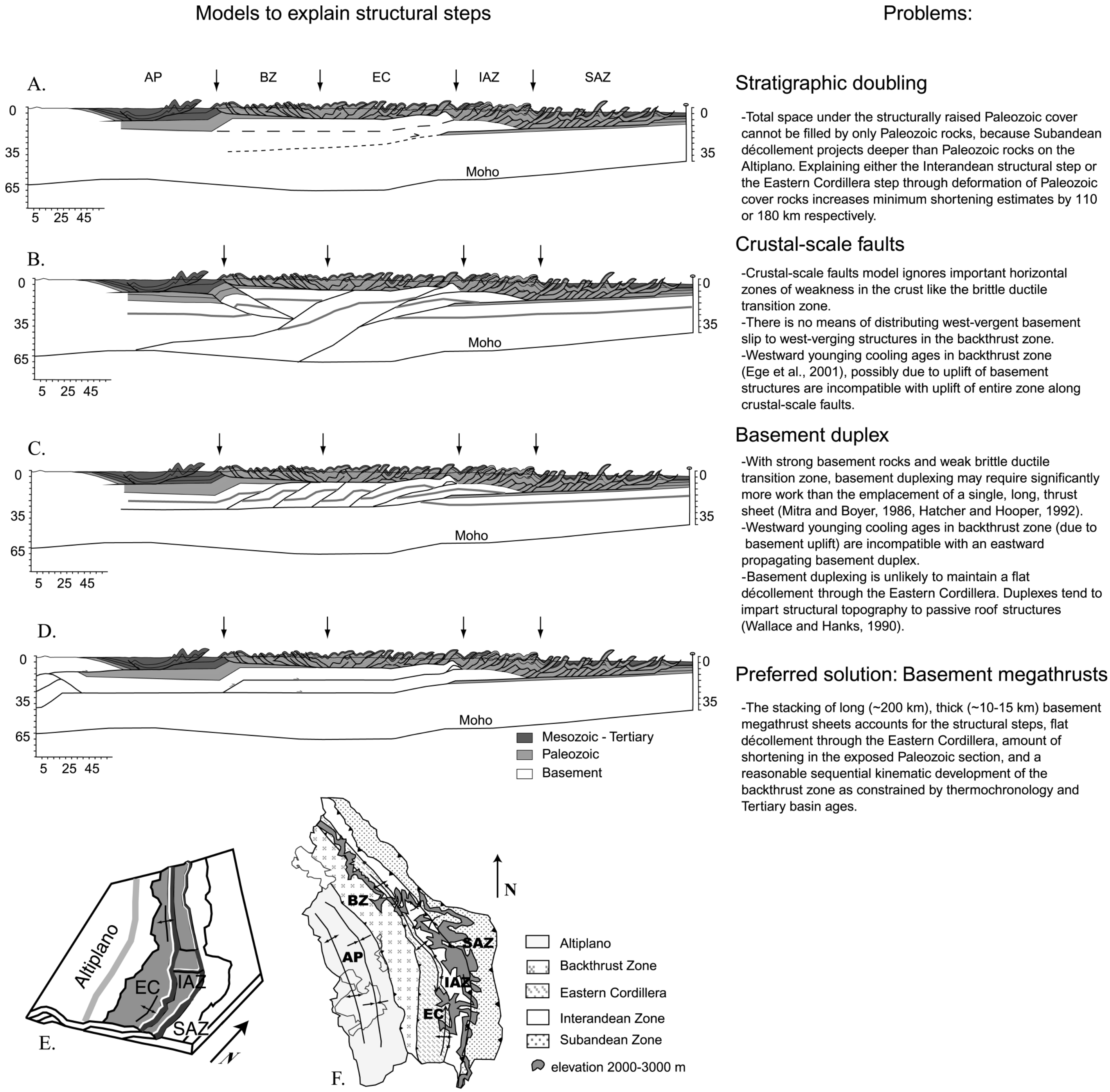

Figure 5. (A–D) Models explaining structural steps in the Andean fold-thrust belt. Arrows mark boundaries of the tectono-structural zones: AP—Altiplano, BZ—backthrust, EC—Eastern Cordillera forethrust, IAZ—Interandean, and SAZ—Subandean. (A) Space above large dashes is area that would need to be filled to account for the Eastern Cordillera structural high. The small dashes show the westward extension of the Subandean décollement. The décollement projects deeper than the lowest elevation of Paleozoic rocks in the hinterland, indicating that the Paleozoic rocks in the backthrust belt cannot have the same décollement as those in the Subandean zone. (B–C) The heavy gray line in the basement is a passive marker that highlights geometry. (E) Structural elevations due to the overlap of basement megathrusts (Paleozoic cover not shown) (modified from Kley, 1999). (F) Correlation between the structural elevations of the basement megathrusts, the tectono-structural zones, and major topographic steps in topography (modified from Kley, 1999). In the south, there is a strong correlation between the Interandean zone and topographic elevations of 2000–3000 m. In the north, the break in elevation occurs in the Eastern Cordillera (Kley, 1999).

Interandean Zone

The first structural step is from the Subandean zone to the Interandean zone (Fig. 5). Kley (1996) defined the Interandean zone as an area of ''thin skinned'' deformation that is structurally elevated with respect to the Subandean zone to the west (Figs. 3, 4, and 5). The tight deformation within the Interandean zone requires a décollement level that is shallower than the décollement projected from the Subandean zone (Fig. 5A). In southern Bolivia, support for the basement thrust sheet as an explanation for the structurally raised décollement horizon comes from gravimetric and magnetotelluric data (Kley et al., 1996; Schmitz and Kley, 1997) and a pronounced gravity anomaly correlated with a seismic refraction discontinuity (Wigger et al., 1994; Dunn et al., 1995). Images of the footwall ramp of this basement thrust sheet are seen on seismic lines (Allmendinger and Zapata, 2000) and are also seen in the regional geologic trends of the fold-thrust belt. Similar to cross sections across southern Bolivia (~21°–22°S) (Kley, 1996), the broad axis of the Sama-Yunchará structural high is interpreted here to trace the upper edge of a major footwall ramp (the footwall ramp for the Interandean basement thrust), and the axis of a series of synclines (Camargo, Otavi, Betanzos, and Maragua synclines) (Figs. 1, 3, and 4) follows the lower edge of the ramp (Kley et al., 1996; Kley, 1996; Allmendinger and Zapata, 2000).

Although space between the Subandean and Interandean décollement horizons could be filled through duplexing of the sedimentary section, this duplex system would add an additional 110 km of shortening (Kley, 1996) that would need to have been erosionally removed from the present-day fold-thrust belt. A simpler approach is to fill the space with a single basement thrust sheet (Kley et al., 1996) and transfer the slip from that thrust sheet into the structures of the Subandean zone. In northern Bolivia, this major basement thrust sheet can account for the elevated level of basement at the northern edge of the Subandean zone (Fig. 3, #5), which suggests that the shortening within the Subandean zone is accommodated by motion along this thrust.

Eastern Cordillera

The structurally highest area of the Andean fold-thrust belt is the Eastern Cordillera, which is raised with respect to both the Interandean zone and the Altiplano (Kley, 1996; Kley et al., 1997; McQuarrie and DeCelles, 2001). The eastern structural step is defined by an almost uniformly dipping succession of Cambrian/Lower Ordovician through Upper Devonian rocks (Geobol, 1992), which are traceable along the entire eastern edge of the Eastern Cordillera (Fig. 1). In southern Bolivia (~21°–22°S), this panel of eastward dipping rocks is the eastern limb of the Sama-Yunchará anticlinorium (Fig. 1). Although the Sama-Yunchará anticlinorium proper plunges to the north and dies out just north of 21°S (Fig. 1) (Geobol, 1992), a series of other en echelon structural highs continue the trend of the Sama-Yunchará anticlinorium to the north and northwest (Fig. 1), indicating the regional importance of this structure. The western limb of the anticlinorium is the series of synclines above the footwall ramp described in the Interandean section above. The western limit of the Eastern Cordillera structural high is the boundary between the lower Paleozoic rocks and Tertiary synorogenic sediments exposed on the eastern edge of the Altiplano (Fig. 1). Minimum depth to the base of the Paleozoic section in the Eastern Cordillera and the Altiplano requires a 12 km step between the two provinces (McQuarrie and DeCelles, 2001). Concurrent with the 12 km structural step is a >100-km-long, northwest-trending gravity anomaly on the U.S. Geological Survey and Geobol gravity map (Cady, 1992; Cady and Wise, 1992). The gravity map shows a 50–70 mgal gravity increase over a 50–60 km distance, which suggests higher density material closer to the surface under the Eastern Cordillera. Although this 12 km Eastern Cordillera structural step can be accommodated by structurally doubling the Paleozoic section (Fig. 5A), doubling the Paleozoic section does not match gravity anomalies or large-scale structural trends and adds at least 180 km of additional shortening to minimum estimates for the central Andean fold-thrust belt.

The discussion above suggests the importance of basement involvement, but it does not place limits on the geometry of the basement structures. Figure 5, B–D, shows three end-member basement deformation styles. Although Figure 5, B and C, accounts for the structural steps noted in the overall geometry of the fold-thrust belt, shortening accommodated in basement rocks (80–160 km, respectively) falls short of accounting for shortening documented in the cover rocks. Other kinematic and geometric problems with these two basement styles include strength differences above and below the brittle-ductile transition zone, difficulty in accounting for the kinematics of west-vergent structures, a flat décollement at the base of the Paleozoic section, and westward-younging cooling ages (Fig. 5).

The preferred mechanism to account for the Eastern Cordillera structural step is through a second, higher-level basement megathrust that is ~12 km thick and ~180 km long (Figs. 3, 4, and 5D). Within the study area, the western limbs of the doubly plunging Incapampa, Tarabuco, and Cochabamba synclines (Figs. 1, 3, and 4) mark the eastern limit of the basement thrust. The footwall ramp of the basement megathrust proposed to structurally raise the Eastern Cordillera is the 12 km structural step between the Altiplano and the Eastern Cordillera.

Basement Megathrusts

The pronounced structural steps in the Bolivian Andes imply a unique basement geometry (Fig. 5E). The large-scale structural, morphological, and topographic features of the Andean fold-thrust belt (and thus the Andean plateau) can be best explained by the duplexing and stacking of long (~200 km), thick (~10–15 km) basement megathrust sheets. This first-order geometry is most readily seen in Figure 5E, where the Andean plateau and associated fold-thrust belt are stripped of the tightly deformed Paleozoic and younger cover rocks. There is a threefold stacking of basement rocks (the Eastern Cordillera basement thrust on the Interandean basement thrust on the Brazilian craton) within the eastern portion of the fold-thrust belt and a proposed basement duplex in the hinterland. The edge of the Andean plateau as defined by the 3 km topographic contour is roughly coincident with the eastern edge of the upper basement thrust sheet in the east and the western edge of the basement duplex in the west. The Altiplano is a structural depression between two basement highs that has been infilled with sediments since the structural damming of its eastern margin (Sempere et al., 1989, 1990; Kennan et al., 1995; Lamb and Hoke, 1997; Rochat et al., 1999; McQuarrie and DeCelles, 2001.)

Basement megathrusts, such as those described previously in the central Andean fold-thrust belt, are common in the medial to hinterland parts of major orogenic wedges. Examples of megathrusts in other orogens include the Blue Ridge–Piedmont sheet (350 km long, 2–12 km thick; southern and central Appalachians; Mitra, 1978; Hatcher and Hooper, 1992; Boyer and Elliott, 1982), Canyon Range and Willard thrust sheets (~100 km long, 2–15 km thick, Cordilleran fold-thrust belt; Mitra, 1997), and the Main Central thrust (140–210 km long, 15–20 km thick, Himalayan fold-thrust belt; Schelling, 1992). The thickness and extent of such huge thrust sheets can be attributed to the strength of the rocks they carry. The rocks contained in megathrust sheets are typically very strong (crystalline basement or thick, uniform sheets of quartzite) with respect to their décollement. The main décollement surface for crystalline mega-

TABLE 1. TABLE OF SHORTENING ESTIMATES FOR THE NORTHERN AND SOUTHERN CROSS SECTIONS

	Length		Shortening	
	Original (km)	Final (km)	(km)	(%)
Northern				
Subandean	131	59	72	55
Interandean	87	48	39	44
Eastern Cordillera				
Backthrust	308	166	142	46
Altiplano	222	174	47	22
Upper basement sheet			181	46
Lower basement sheet			72	55
Total	748	448	300	40
Southern				
Subandean	206	139	67	33
Interandean	152	56	96	63
Eastern Cordillera	178	112	66	37
Backthrust	152	96	56	37
Altiplano	194	153	41	21
Upper basement sheet			218	45
Lower basement sheet			67	33
Total	882	556	326	37

thrusts is the thermally weakened brittle-ductile transition zone (Hatcher and Hooper, 1992).

Amount of Shortening

Restoration of balanced cross sections provides a minimum estimate of horizontal shortening along transects through the Andean fold-thrust belt. The shortening estimates were made for each of the zones presented here, illustrated in Figures 3 and 4 and shown in Table 1. The combined shortening of the Interandean zone and the Eastern Cordillera zones (both forethrust zone and backthrust zone) was accommodated by shortening on the higher basement thrust. For the northern cross section, this displacement is 181 km or 46% shortening, and in the southern cross section, this shortening is 218 km or 45%. The slip from the upper basement thrust sheet is by far the most extensive. The lower basement thrust sheet only accommodates slip within the Subandean zone (67–72 km). Although the cumulative slip on the basement faults themselves is significant (67–218 km), the emergent faults along the eastern boundary of the Interandean zone and the Subandean zone have slip magnitudes on the order of 5–10 km. The total shortening for both cross sections is 300–330 km.

KINEMATIC HISTORY

The sequential kinematic evolution of the Andean fold-thrust belt along the northern and southern lines of cross section is depicted in Figures 6 and 7. The proposed evolution is based almost entirely on the geometric constraints of the structural cross sections presented in Figures 3 and 4, but is consistent with available basin migration history (Horton et al., 2001; DeCelles and Horton, 1999), ages of overlapping syntectonic sedimentary rocks (Sempere et al., 1990; Jordan et al., 1997), and local thermochronology (Benjamin et al., 1987; McBride et al., 1987; Farrar et al., 1988; Sempere et al., 1990; Masek et al., 1994). The kinematic cross sections were constructed under the assumption that the faults are in-sequence in the direction of transport whenever possible. The most obvious departure from this assumption is the zone of eastward-verging ''backthrusts'' within the southern cross section. This anomalous zone is discussed further in a later part of this paper.

Due to the foreland-ward migration of fold-thrust belts with time, and the prevalence of volcanic cover throughout the western Andes, constraints for the onset of mountain building within the Bolivian Andes are most readily identified by the age of the oldest sediments derived from the growing orogenic wedge. Thus, the recognition of Late Cretaceous to late Eocene backbulge and forebulge foreland basin deposits (DeCelles and Giles, 1996) along with a late Eocene to Oligocene foredeep within the Altiplano and Eastern Cordillera strongly suggests that a fully developed fold-thrust belt and foreland basin system existed in Chile and/or westernmost Bolivia in Late Cretaceous–Paleocene time and that this fold-thrust belt propagated eastward with time to create the modern Andean fold-thrust belt (DeCelles and Horton, 1999; Horton et al., 2001). I propose that this early fold-thrust belt jumped eastward by carving off an ~300-km-long basement thrust sheet along the brittle-ductile transition zone, and that this basement fault subsequently controlled the large-scale evolution of the fold-thrust belt (Figs. 6 and 7).

The kinematic sequence starts with the eastward propagation of the fold-thrust belt along the brittle ductile transition (~15 km depth) and the extension of the basal detachment ~300 km to the east. In the north, this basal thrust cut up through the basement earlier (~200 km) but then propagated eastward again along the Lower Ordovician shale another ~250 km before it breached the surface (Fig. 6, steps 1–2a). Perhaps because of the dramatic overextension of the fold-thrust belt, the first series of structures to form were roof thrusts in the mechanically strong Upper Ordovician formations and duplexes in the weak Lower Ordovician formation, which created a local topographic and structural high (Fig. 6, step 2a). Evidence for a western basement thrust with minimal slip (~20 km) is taken from both the intermediate step in the level of the Paleozoic under the Lago Poopo basin (Fig. 3) (McQuarrie and DeCelles, 2001) and the erosion of as much as 3–5 km of Cretaceous through Oligocene strata from this narrow, 40-km-wide area. About 20 km of slip was transferred up this western ramp before a new fault developed along the brittle-ductile transition zone and created a new basement ramp ~170 km to the east (Fig. 6, step 2b). In the south, the detachment climbed directly from the basement to the surface. Slip from the detachment was accommodated by a series of eastward-propagating thrusts (Fig. 7, step 2). Evidence for inception of basement thrusting is loosely bracketed by thermochronologic data. Sparse thermochronologic data from zircon fission track and $^{40}Ar/^{39}Ar$ cooling ages suggest exhumation in the Eastern Cordillera at ca. 40 ± 5 Ma (Benjamin et al., 1987; McBride et al., 1987; Farrar et al., 1988; Sempere et al., 1990; Masek et al., 1994). This late Eocene–early Oligocene cooling event could represent the uplift of the Eastern Cordillera as the basement thrust propagated up and over the basement ramp that defines the edge of the Altiplano piggyback basin.

Time step 3 in both the north and the south (Figs. 6 and 7) shows the development of the backthrust zone. In the north, the formation and propagation of west-verging thrusts and folds most likely developed in order to build topography and thus increase taper between the basement high to the west and the Ordovician duplex high to the east (Fig. 6, step 3). In the south, this section of the backthrust zone is composed of four to five east-verging, out-of-sequence (in the direction of transport) faults and associated folds that accommodated 30 km of shortening along the basement thrust (Fig. 7, steps 3 and 4). These faults are essentially double wedge fault systems where the east-directed slip from the basement thrust

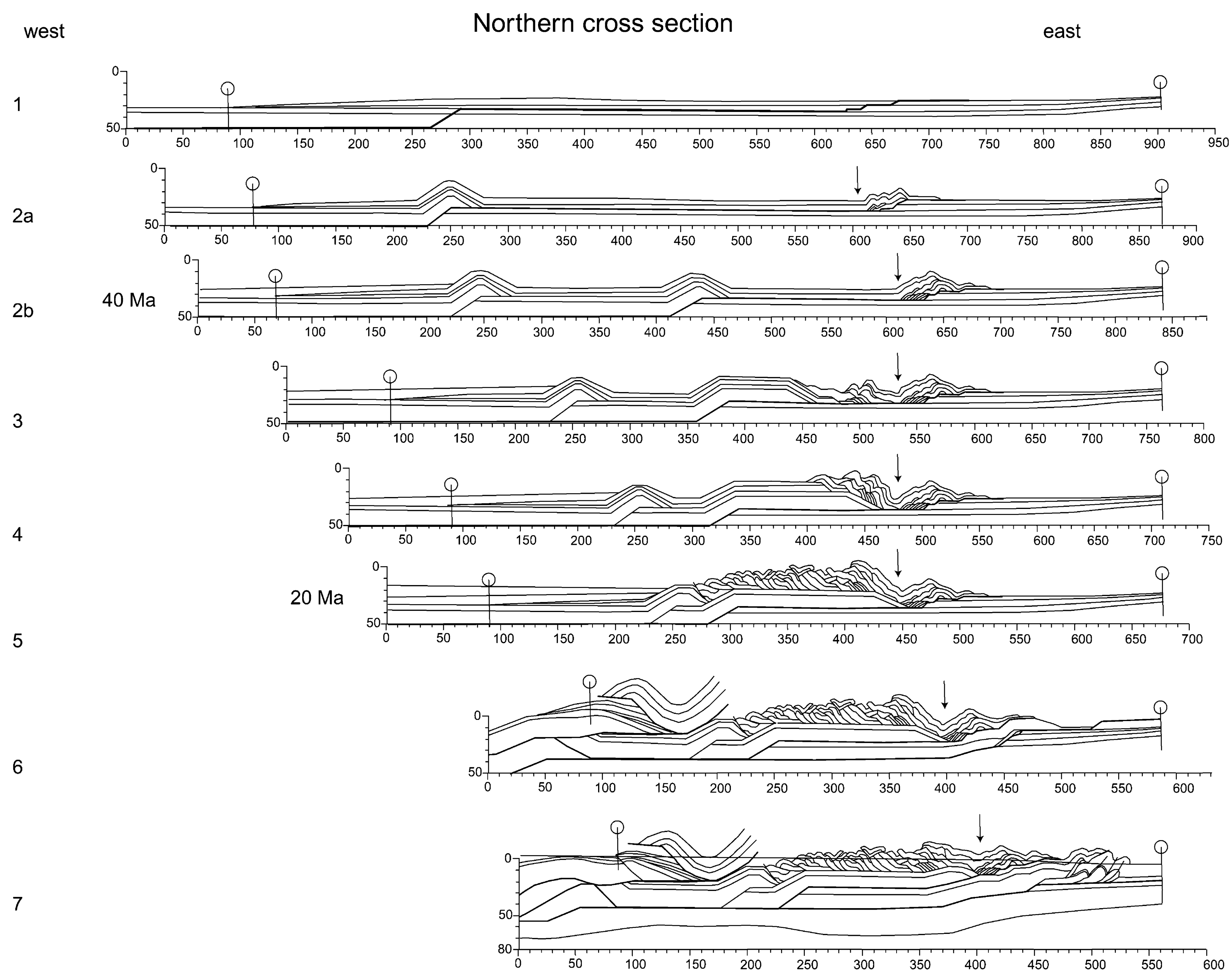

Figure 6. Kinematic evolution diagram showing the structural development of the northern cross section. The restored section (Fig. 3) is sequentially deformed in eight steps. Dates indicate local timing constraints, and arrow shows the location of the Cochabamba area with time. Scale is in kilometers with no vertical exaggeration.

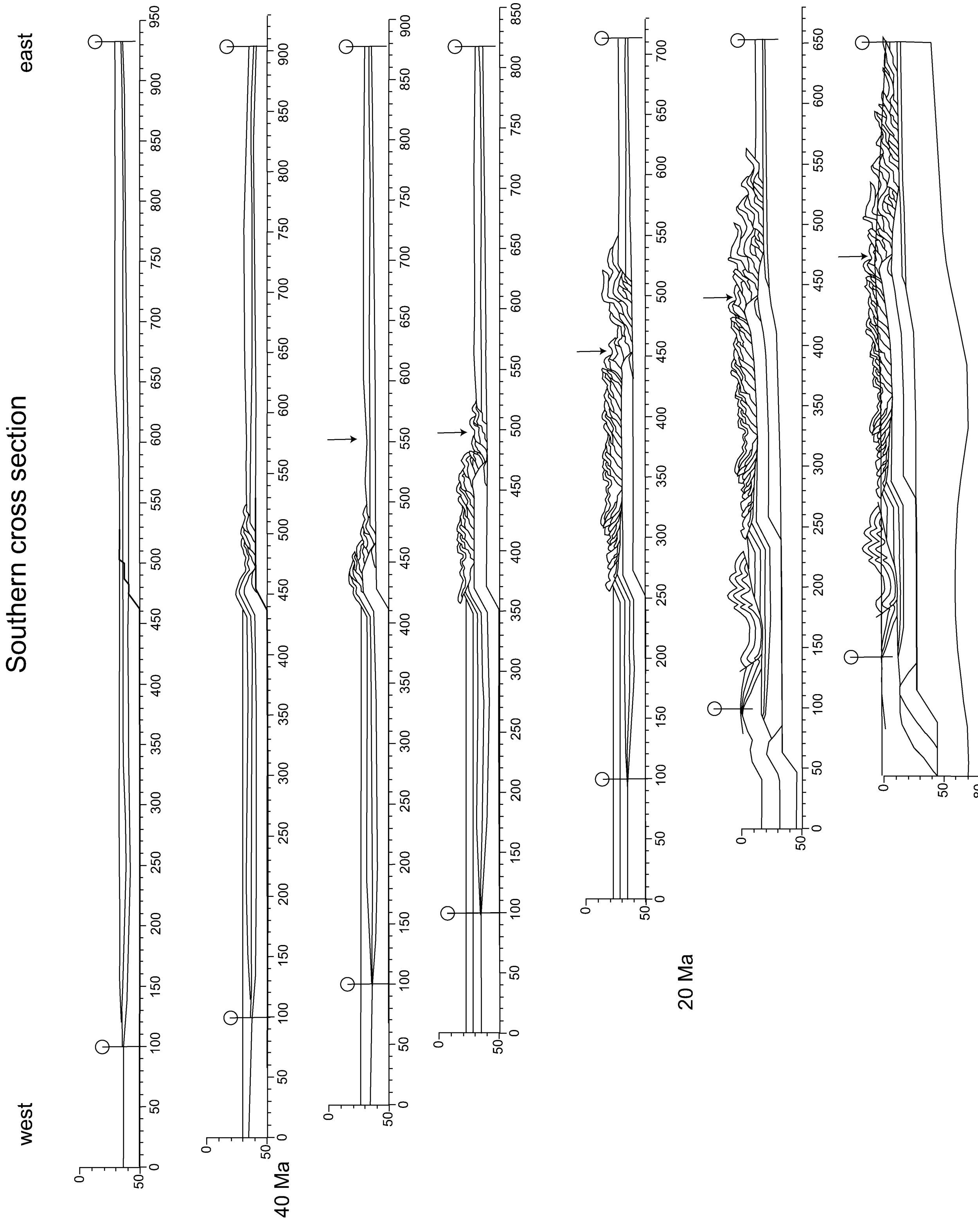

Figure 7. Kinematic evolution diagram showing the structural development of the southern cross section. The restored section (Fig. 4) is sequentially deformed in seven steps. Dates indicate local timing constraints, and arrow shows the location of the Tarabuco and Incapampa synclines (or eastern edge of the Andean plateau) with time. Scale is in kilometers with no vertical exaggeration.

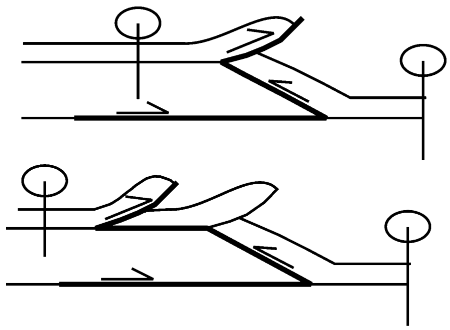

Figure 8. Evolution of double-wedge fault systems. Bold line indicates active fault, pins mark areas of no slip. Slip from the wedge top is transferred into out of sequence faults in cover rocks.

was taken up by west-directed slip on the basement cover interface above the basement thrust. In turn, west-directed slip was transferred to east-directed thrust faults that propagated through cover rocks to a structurally higher level (Fig. 8).

Time steps 4 and 5 show the continued development of the in-sequence, westward-verging and propagating backthrust zone. The backthrust zone functioned as a complex, passive roof sheet to the eastward wedging basement thrust beneath it. In the north, the slip on the upper basement fault (~140 km) was taken up in the cover by the backthrust belt. Similar amounts of slip in the south (~150 km) are taken up by both west-verging structures in the backthrust belt and east-verging structures in the Interandean zone. Fold-thrust structures in the northern portion of the backthrust zone are overlapped by mildly deformed sedimentary rocks of the Salla beds (Sempere et al., 1990), which are dated between 24 and 21 Ma (McFadden et al., 1985; Sempere et al., 1990). Both the backthrust belt and the Interandean zone are linked by slip on the upper basement fault. Synorogenic sedimentary rocks, which give an upper age limit for the youngest deformation within the backthrust zone, also provide an age limit for the duration of slip on the upper basement fault and, thus, the age of deformation within the Interandean zone. This suggests that deformation within the Interandean zone is much older than 10–5 Ma, as previously proposed (Kley, 1996).

Coeval deformation within the Altiplano and in the Subandean zone is shown in time step 6. "Out-of-sequence" basement thrusting and the development of the proposed basement duplex deformed the piggyback basin of the Altiplano. The eastern limb of the Corque syncline may have been folded initially as a fault-bend fold over the basement ramp. In time step 6 (Fig. 6), continued deformation of the syncline was accomplished by out-of-sequence basement slip fed eastward into the east-verging faulted limb of the syncline, which steepened the dip and moved the old unconformities through the erosion surface. The second stage of syncline development included rotation and out-of-the-syncline faulting of the western limb through continued growth of the duplex. Evidence to support a two-stage folding of the Corque syncline includes the presence of conformable beds from 55 through 9 Ma on the western limb, and an angular unconformity (ca. 9 Ma) on the east limb (Lamb and Hoke, 1997). Slip created from the growth of the duplex was transferred eastward along the lower basement fault into the Subandean zone. This thrust uplifted the Interandean zone with respect to the foreland while deforming the foreland into the open synclines and the tight anticlines that characterize the Subandean zone. Growth and development of the Altiplano fold belt shown in Figure 7 (time step 6) were accomplished through similar mechanisms. The modern fold-thrust belt, complete with crustal thickness from Beck et al. (1996), is shown in time step 7.

CRUSTAL THICKENING BUDGET

The origin of the thick crust that underlies the central Andean plateau has been the focal point of several studies during the last 20 yr, and most authors attributed the thickness of the plateau to pervasive tectonic shortening of the crust (Isacks, 1988; Sheffels, 1990; Schmitz, 1994; Lamb and Hoke, 1997). Previous estimates of crustal shortening can account for as much as 70%–80% of the present crustal volume of the plateau (Sheffels, 1990; Lamb and Hoke, 1997; Kley and Monaldi, 1998). The correlation is best for the central portion of the plateau (~18°–21°S) but diverges dramatically to the north and south (Kley and Monaldi, 1998). The 60–70-km-thick crust of the Andean plateau is predominantly felsic (Zandt et al., 1994; Beck et al., 1996, Swenson et al., 2000), which suggests that a more mafic lower crust is missing. This implies that shortening estimates should account for the thickness of the felsic crust and some portion of more mafic lower crust that has been lost or altered through time (Beck and Zandt, 2002). To this end, it is important to determine the contribution of each of the zones described above to the total crustal thickness budget of the Andean plateau. It is then possible to evaluate whether shortening within the Andean fold-thrust belt can account for both the observed crustal thicknesses and the amount of crustal material lost through either crustal flow (thickening the northern and southern limits of the plateau), or delamination or alteration of a more mafic lower crust.

The shortening and crustal thickening budget for each of the five zones was calculated using the original and final lengths of each zone and the original and final thicknesses in order to ascertain both the present-day area (A) and the potential area (P) (Fig. 9 and Table 2). The present-day thickness numbers used in the area calculations (Table 2) were determined by estimating the average thickness of the individual zones (using crustal thickness values from Beck et al. [1996] and Beck and Zandt [2002]) and by estimating the additional thickness of crust lost to erosion (by accounting for the bed lengths that are projected above the erosion surface on the cross sections). Thus, the final thickness (Tf) used in the calculations is 5–15 km thicker than present-day crustal thicknesses (Tp) (Table 2). The lengths used in the calculations are the final length or present-day length (Lf) of the zones on the cross section. In calculating the potential or original area for each zone, the largest unknown is the original thickness of the crust. The original thickness of the Subandean, Interandean, and Eastern Cordillera forethrust and backthrust zones is estimated to have been 35–40 km. The upper estimate, 40 km, is based on using the modern foreland basin as an undeformed template. Seismic reflection, and refraction and receiver function analysis combined with industry well data suggest that this 40-km-thick crust can be divided into an ~30-km-thick basement, an ~6–8-km-thick section of Paleozoic–Mesozoic sedimentary rocks, and an ~3-km-thick section of foreland basin sediments (Wigger et al., 1994; Dunn et al., 1995; Welsink et al., 1995; Beck et al., 1996; Beck and Zandt, 2002). Although there is pre-Andean loss of upper Paleozoic sedimentary rocks to the west, Paleozoic rocks as a whole thicken to the west (Figs. 3 and 4), which suggests that a 35–40-km-thick original crust is a conservative estimate. The original thickness of the Altiplano is estimated to be 50 km. The 10 km extra thickness is to account for the 10+ km of infilled Tertiary syntectonic sediments. The undeformed length of each zone was taken off the undeformed template produced by balancing the cross sections (Figs. 3 and 4). The difference between the present-day area (plus eroded sediments) and the original or potential area is an area loss or gain for each zone (E) (Table 2, Fig. 9). Figure 9 shows that for the northern cross section, shortening within the Altiplano, Eastern Cor-

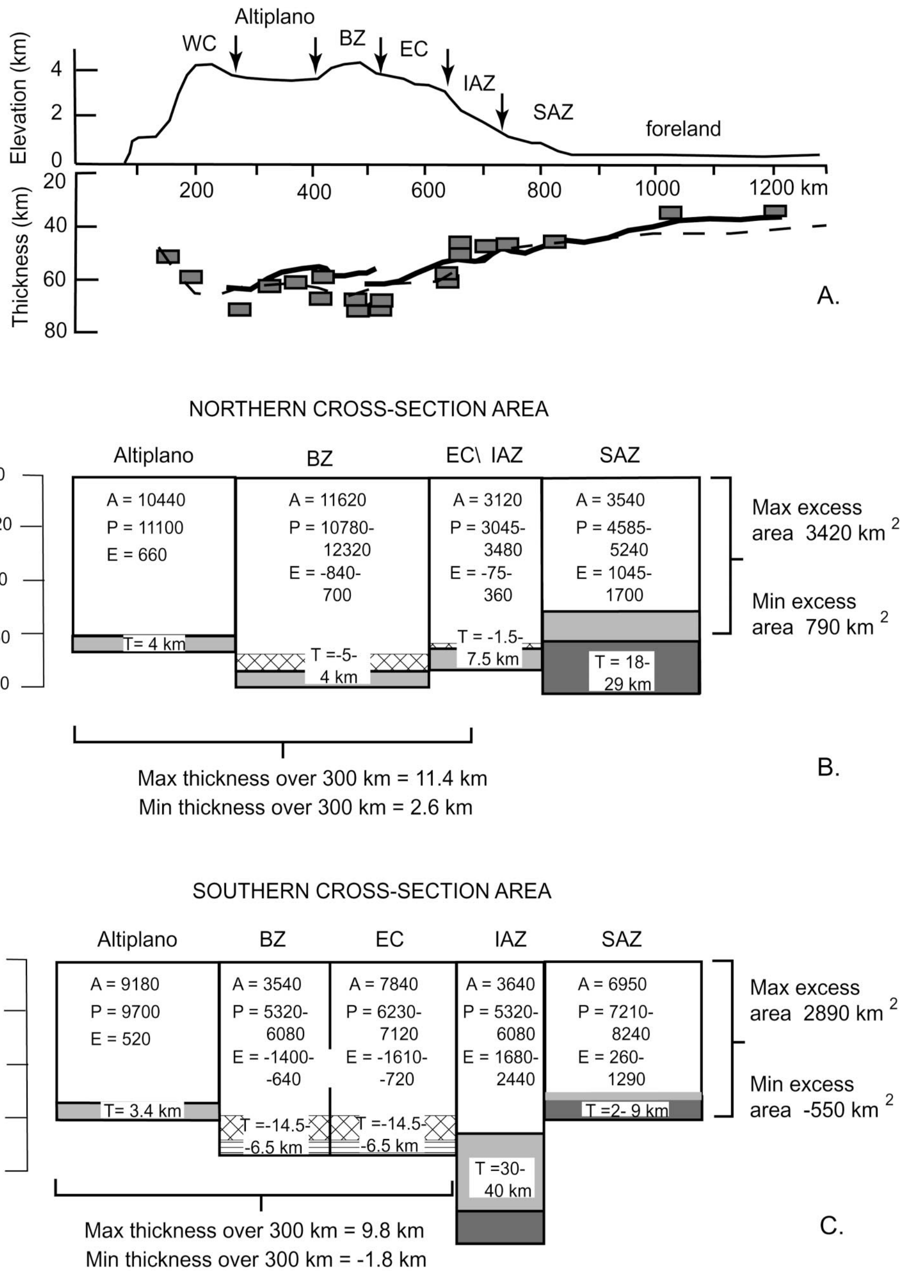

Figure 9. (A) Crustal thickness variation diagram from Beck et al. (1996) Beck and Zandt (2002), with topography (~50× vertical exaggeration), observed crustal thickness (shaded boxes [Beck et al., 1996] and solid line [Beck and Zandt, 2002]), and predicted crustal thickness based on topography in Airy isostatic equilibrium (dashed line) (~5× vertical exaggeration). Arrows mark boundaries of the tectono-structural zones: WC—Western Cordillera, BZ—backthrust, EC—Eastern Cordillera forethrust, IAZ—Interandean, and SAZ—Subandean. (B and C) Box diagram shows crustal thickness budget for the northern cross section, B, and the southern cross section, C. Vertical scale shows thickness variations (no horizontal scale). White boxes indicate present-day crustal thickness (accounting for thickness of rocks removed via erosion), and shaded boxes (light gray for maximum, dark gray for minimum) indicate area gained through shortening not accounted for in present-day crustal thickness. Hachured lines (diagonal for maximum, horizontal for minimum) indicate area deficit or area needed to explain present-day crustal thickness but not accounted for by shortening estimates. Data for area calculations are shown in Table 2 and discussed in text.

dillera (backthrust and forethrust), and Interandean zones can account for the complete crustal thickness of these areas using a 40-km-thick original crust. A 35-km-thick crust gives a 1.5–5-km-thick deficit for the Eastern Cordillera forethrust/Interandean zones and the backthrust zone, respectively. The Subandean zone has an excess thickness of 18–29 km (Fig. 9), which can compensate for a potential deficit in the areas to the west and still allow for a crustal excess of the cross section as a whole. Excess area for the northern cross section ranges from 790 to 3420 km^2, which equates to thicknesses of 2.6–11.4 km over a 300 km length (the approximate width of the Andean plateau). In the southern cross section, shortening within the Eastern Cordillera backthrust and forethrust zones falls short of accounting for the present crustal thickness by 6.5–14.5 km. Most of this difference can be made up through excess area within the Interandean zone, 1680–2440 km^2. Excess area within the southern Subandean zone contributed minimally (260–1290 km^2) to the thickness of the plateau in this region. Excess area for the southern cross section ranges from −550 to 2890 km^2. This equates to a thickness deficit of −1.8 km or a thickness excess of 9.8 km over a 300 km length. Using an original crustal thickness of 35 km, the shortening within the Andean fold-thrust belt can nearly account for the crustal thickness in the southern cross section (1.8 km short over 300 km length) but can more than account for crustal thickness in the northern cross section (4 km extra over 300 km length). Using an original crustal thickness of 40 km indicates an excess in crustal area of 2890–3420 km^2. In this case, ~10 km of crust would need to be lost through crustal flow, delamination, or alteration.

Combining the thickening budgets of each zone with proposed timing constraints (Figs. 6 and 7) gives insights into how the thickness of the Andean plateau evolved through time. Since deformation within the backthrust zone is bracketed by overlap sediments that are dated at ca. 20 Ma, most of the motion on the upper basement slab (and thus deformation within the backthrust, Eastern Cordillera, and Interandean zones) had ended by ca. 20 Ma. This suggests much of the crustal thickness (50–60 km) of the Andean plateau and its physiographic boundaries were obtained by this time.

CONCLUSIONS

1. The formation of the central Andean plateau is linked directly to the kinematic development of the Andean fold-thrust belt, which

TABLE 2. DATA AND RESULTS FOR CRUSTAL AREA CALCULATIONS

	Lo (km)	Lf (km)	To (km)	Tf (km)	Tp (km)	A (km²)	P (km²)	E (km²)
Northern								
Subandean	131	59	35–40	60	45–50	3540	4585–5240	1045–1700
Interandean	87	48	35–40	65	55–60	3120	3045–3480	−75–360
Eastern Cordillera								
Backthrust	308	166	35–40	70	65–70	11620	10780–12320	−840–700
Altiplano	222	174	50	60	60–63	10440	11100	660
Total	748	448				28720	29510–32140	790–3420
Southern								
Subandean	206	139	35–40	50	45–55	6950	7210–8240	260–1290
Interandean	152	56	35–40	65	55–60	3640	5320–6080	1680–2440
Eastern Cordillera	178	112	35–40	70	60–70	7840	6230–7120	−1610– −720
Backthrust	152	96	35–40	70	65–70	6720	5320–6080	−1400– −640
Altiplano	194	153	50	60	60–63	9180	9700	520
Total	882	556				34330	33780–37220	−550–2890

Note: Lo—original length; Lf—final length; To—original thickness; Tf—final thickness (including rocks moved through the erosion surface); Tp—present-day crustal thickness from Beck (1996) and Beck and Zandt (2002); variations reflect changes over lateral distance of zone. A—present-day area (including rocks moved through the erosion surface); P—original area or the potential area based on shortening calculations; E—excess area (negative numbers refer to area deficits).

fundamentally grew via the creation and propagation of two basement megathrusts.

2. Minimum shortening estimates for the central Andean fold-thrust belt are 300 km (40%) along the northern transect and 330 km (37%) along the southern transect; 180–220 km of this shortening were accommodated by shortening along the upper megathrust, which transferred slip into the Eastern Cordillera zone, the backthrust zone, and the Interandean zone. The lower basement megathrust transferred 60–70 km of slip eastward into the Subandean zone.

3. The inferred kinematic development of the central Andean fold-thrust belt suggests that the wide (100+ km) zone of backthrusts developed as a half crustal-scale, passive-roof duplex, perhaps in order to rebuild taper after the first basement megathrust overextended the system eastward.

4. The large-scale structural, morphological, and topographical features of the Andean fold-thrust belt, and thus the Andean plateau, are controlled by the duplexing and stacking of two basement megathrusts. The edge of the Andean plateau as defined by the 3 km topographic contour is roughly coincident with the eastern edge of the upper basement thrust sheet in the east and the western edge of the basement duplex in the west. The proposed relationship between the basement thrusts and the physiographic boundaries of the Andean plateau suggests that extensive megathrust sheets (involving strong rocks such as crystalline basement or quartzite) are one of the primary controls on the formation of the Andean plateau.

5. Crustal thickening associated with shortening of the Andean fold-thrust belt can account for the total crustal thickness of the Andean plateau and suggests that ~10 km of crustal material may have been lost due to crustal flow, or delamination or alteration of a mafic lower crust.

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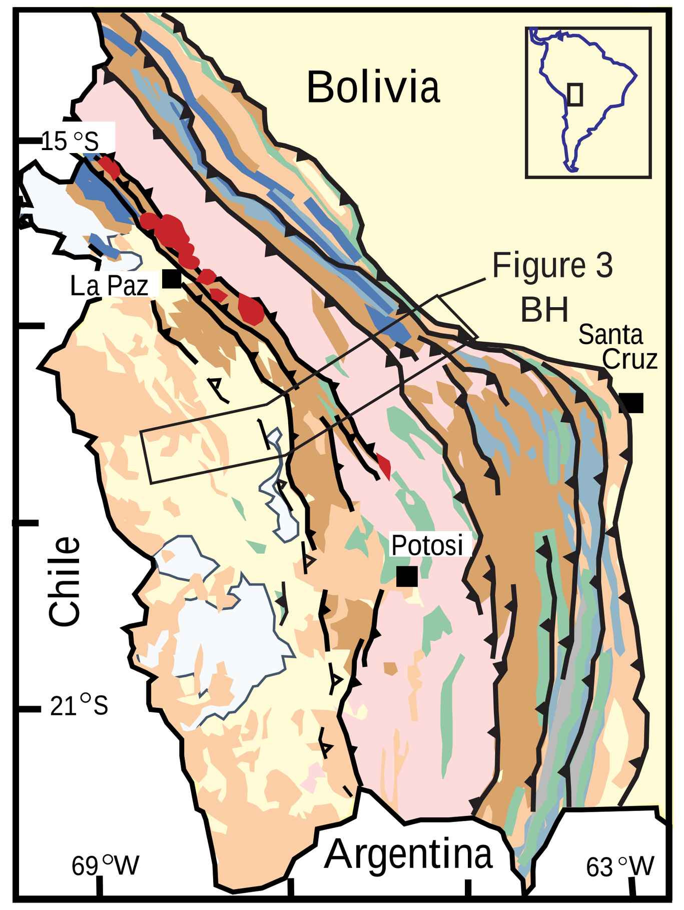
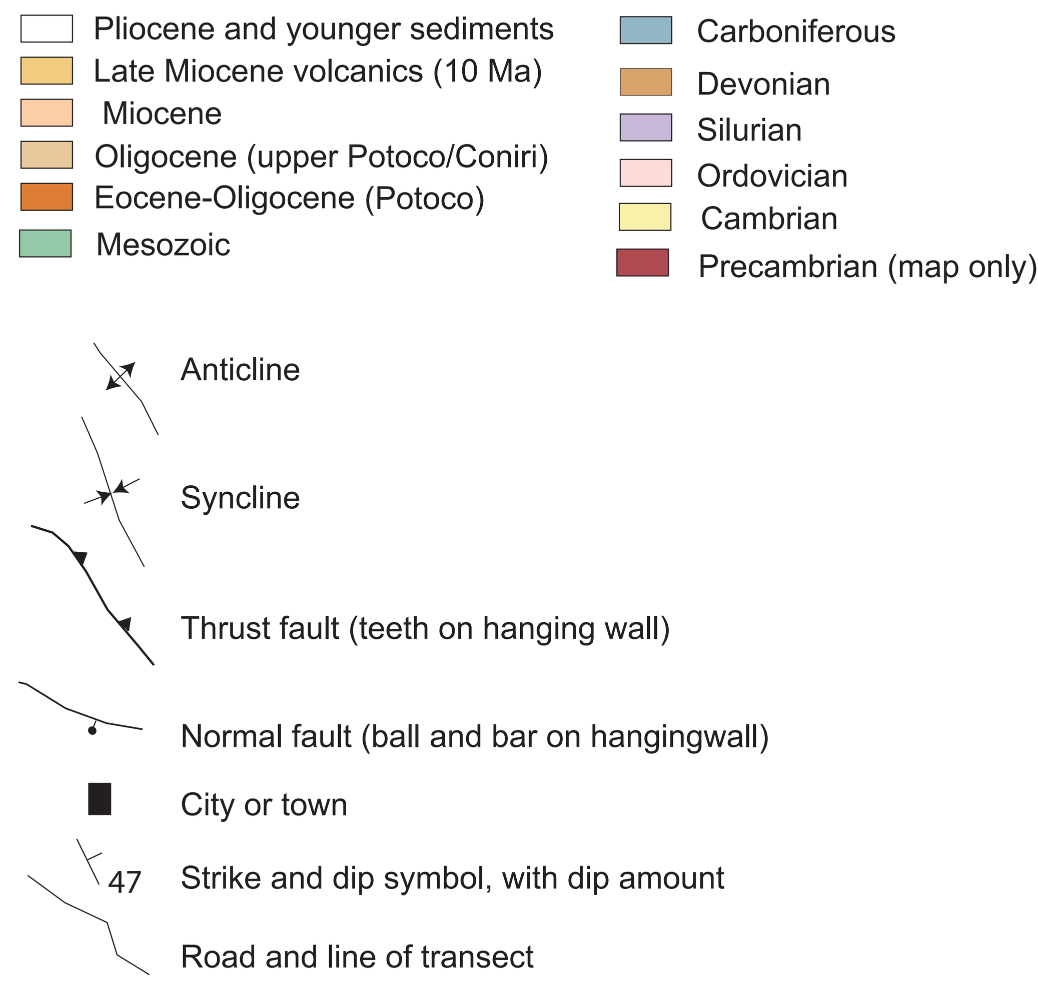
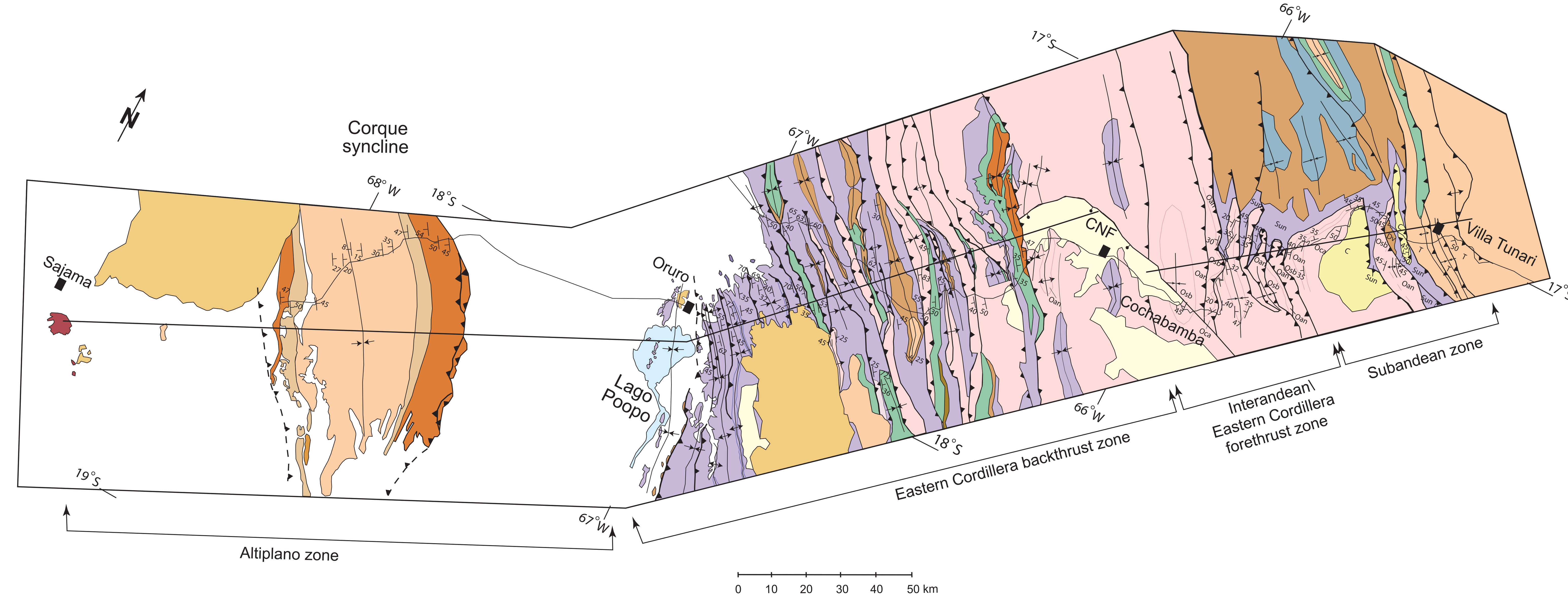
Figure 3 Northern cross section

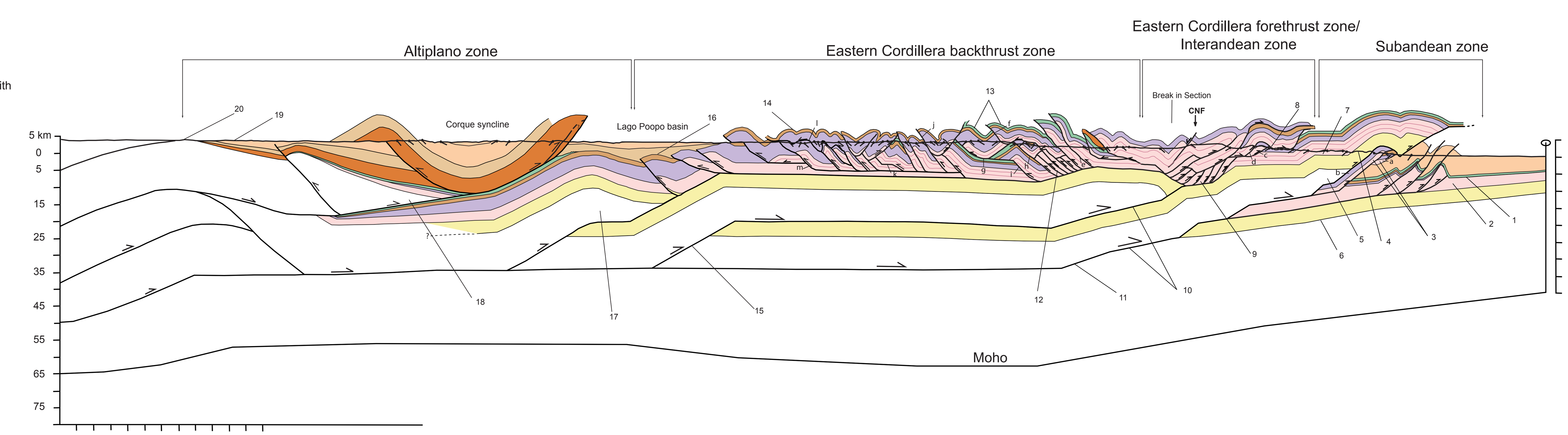


Index map for Figure 3





1. Thickness of foredeep and slope (4°) on basement determined from Industry well data and seismic reflection lines in the Boomerang Hills region (BH, index map) and in the Isiboro region(~40 km north of cross section line) (Baby et al., 1995; Welsink et al.,1995; Roeder and Chamberlain, 1995).
2. Thickness of Ordovician towards foreland is unknown, as well as detachment level of the frontal thrust. However, in the northern Subandean zone the Ordovician constitutes the "effective" basement on seismic lines and well data (Welsink et al., 1995), and the lower Ordovician shales are a major decollement for the fold-thrust belt (Baby et al., 1995; this paper).
3. Horses of upper Ordovician through upper Silurian/lower Devonian rocks feed slip into the Cambrian/basement thrust sheet.
4. Minimum thickness of exposed Cambrian rocks from map data.
5. Minimum depth to basement under exposed Cambrian rocks.
6. Increase in slope of basement decollement from 4° to 10° proposed due to basement load. The increase in dip is necessary to extend complete Cambrian through Silurian section under basement thrust sheet. Significant increases in dip of decollement towards hinterland is recognized in other orogens (Hauck et al., 1998).
7. Wide zone of Capinota Formation (lowermost Ordovician) exposed at surface with bedding attitudes of N 40° E to N 70° E dipping 35° to the northwest.
8. Presence of Ordovician hangingwall flat on Silurian (Uncia Formation) footwall flat is supported by map pattern of repeating Ordovician Anzaldo Formation on Silurian Uncia Formation with Ordovician rocks exposed on ridges and Silurian rocks exposed in valleys. The long flat is also supported by folded Anzaldo Formation klippe on upper Ordovician San Benito Formation to south (see map).
9. Inferred horses in lower Ordovician rocks are needed to balance bed length in upper Ordovician Anzaldo and San Benito Formations. Excess length in these rocks is based on repeating Anzaldo Formation on San Benito or Uncia Formations with hangingwall flat on footwall flat relationships.
10. Increase in slope of the basement decollement from 10° -13° minimizes the antiform caused by the alignment of hangingwall ramp with footwall flat, and hangingwall flat with footwall ramp.
11. Footwall ramp for lower basement thrust sheet based on minimum offset on Cambrian/basement thrust sheet.
12. Horses in lower Ordovician needed to balance excessive bed length of upper Ordovician roof sheet.
13. Ordovician roof sheet is suggested by a map pattern of branching thrust faults (see map) (McQuarrie and DeCelles, 2001).
14. Length of Silurian roof sheet based on fault-bounded syncline of lower Silurian rocks over upper Silurian rocks with conformable bedding attitudes suggesting a hangingwall flat on footwall flat relationship.
15. Location of ramp: Basement ramp is needed to explain ~20 km of offset between Paleozoic rocks exposed within the backthrust zone and those predicted below the Corque syncline. Location of ramp is on the east side of Lago Poopo basin based on Industry seismic reflection lines and structural level of basement under the Lago Poopo basin (McQuarrie and DeCelles, 2001).
16. Structure in Poopo basin based on Industry seismic reflection lines (McQuarrie and DeCelles, 2001). Industry wells in the Poopo basin area indicate 25 Ma syntectonic sedimentary rocks rest on Paleozoic rocks and that Jurassic through Oligocene rocks have been removed.
17. Westward basement thrust/ramp accommodates anticlinal rise of Paleozoic rocks on the west side of Lago Poopo basin immediately east of the Corque-Corocoro syncline. Upper Paleozoic geometry based on seismic data (McQuarrie and DeCelles, 2001).
18. Geometry of east-dipping syntectonic sediments based on seismic lines (McQuarrie and DeCelles, 2001). Basement fault is proposed to accommodate ~40 km of slip on both east- and west- verging faults bounding the Corque syncline.
19. East-dipping and eastward diverging growth structures in 25-5 Ma rocks on seismic reflection lines (McQuarrie and DeCelles, 2001).
20. Precambrian basement rocks at surface. Basement duplex is inferred in order to fill space and raise basement 20 km with respect to syncline.



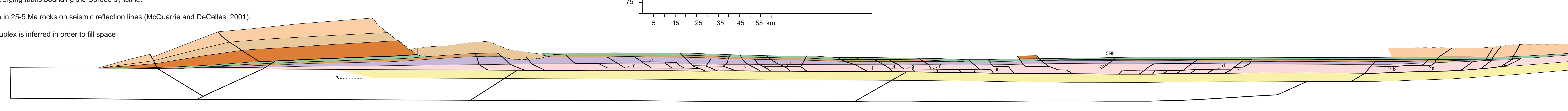
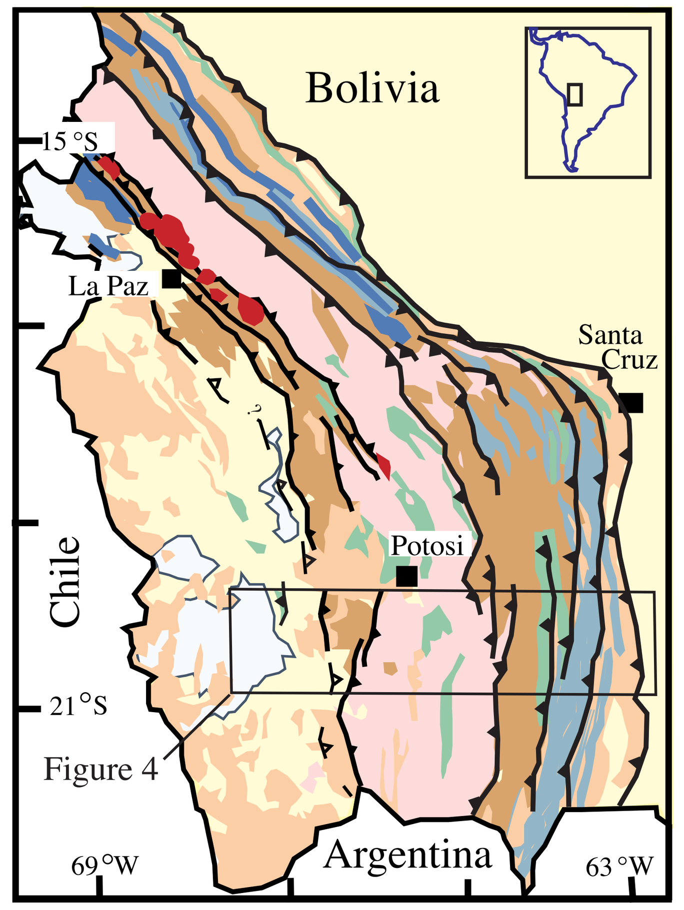


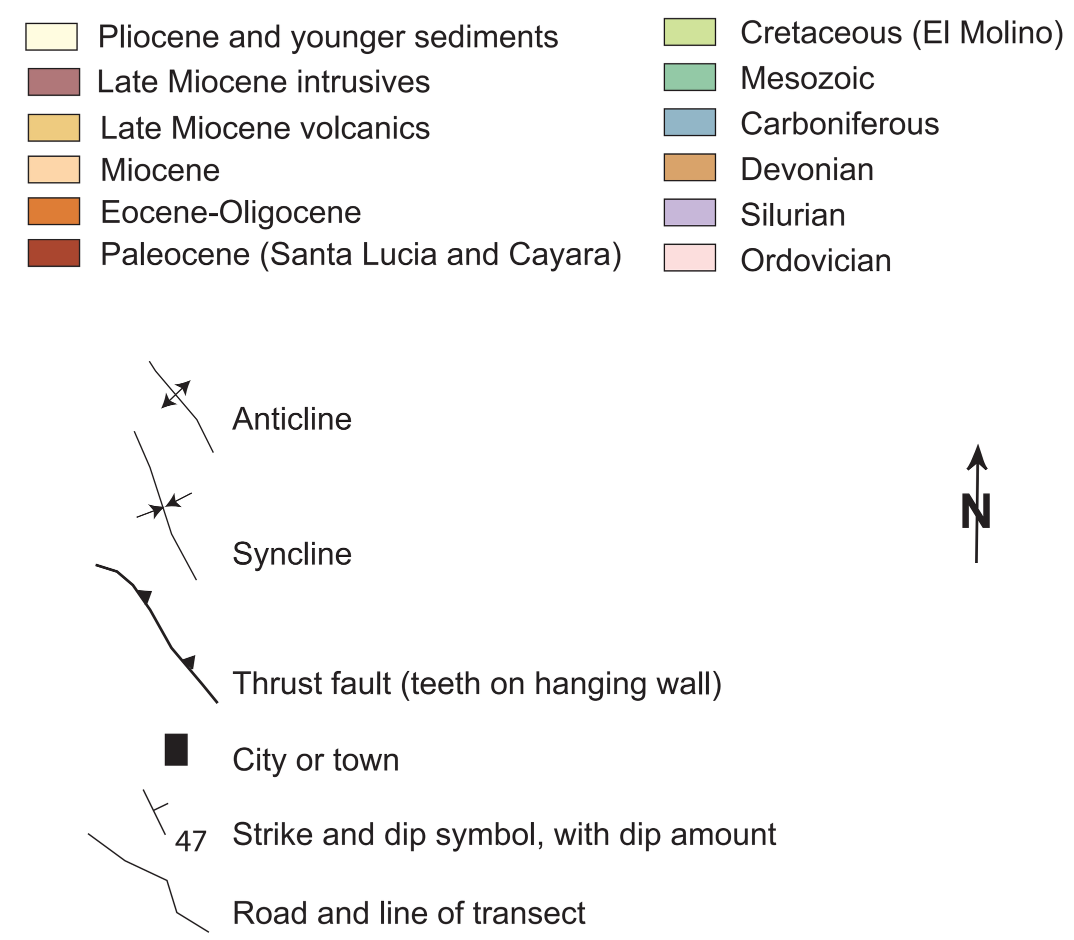
Figure 3
Northern cross-section, restored section and generalized geologic map. The map is simplified from Pareja et al. (1978), Goitia (1994); Geobol (1994; 1995a; 1995b; 1996a); Suarez et al. (2001), with detailed mapping along specified transects superimposed. Major tectono-structural zones identified by brackets. CNF, Cochabamba normal fault. Numbers refer to annotations on left side of plate. Ocp, Oan, and Osb refer to Ordovician Capinota, Anzaldo and San Benito Formations respectively.

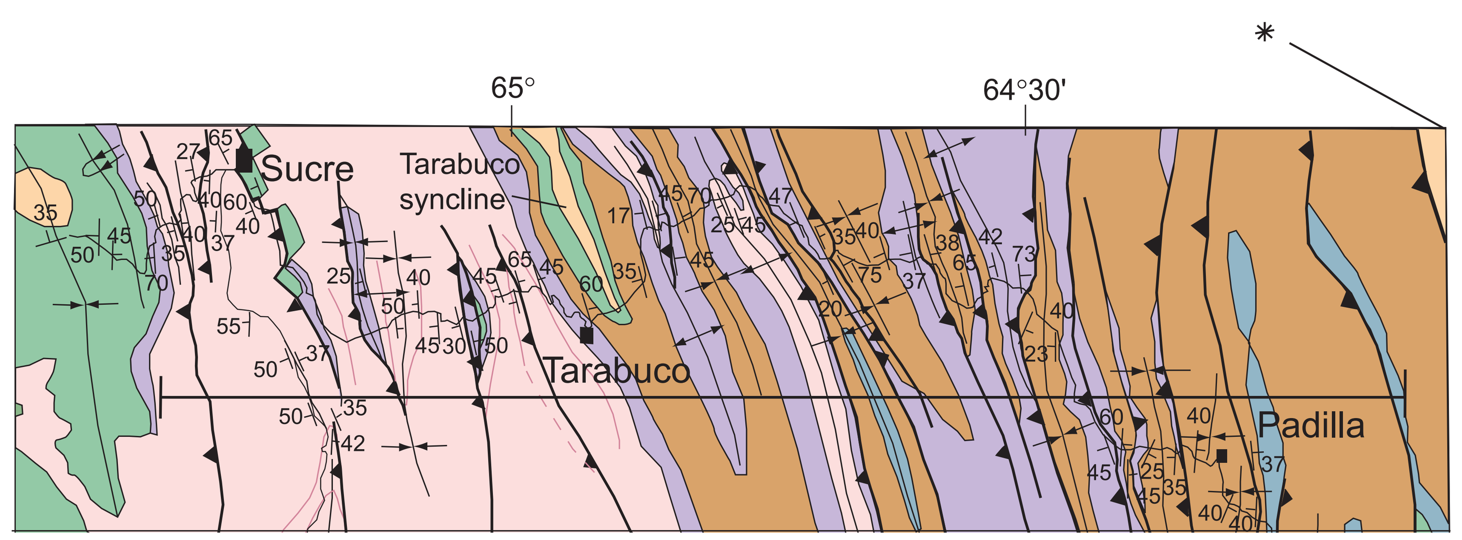
The kinematic history of the central Andean fold-thrust belt, Boliva: Implications for building a high plateau.
Nadine McQuarrie
Figures 3 and 4
Supplement to: Geological Society of America Bulletin, v. 114, no. 8.

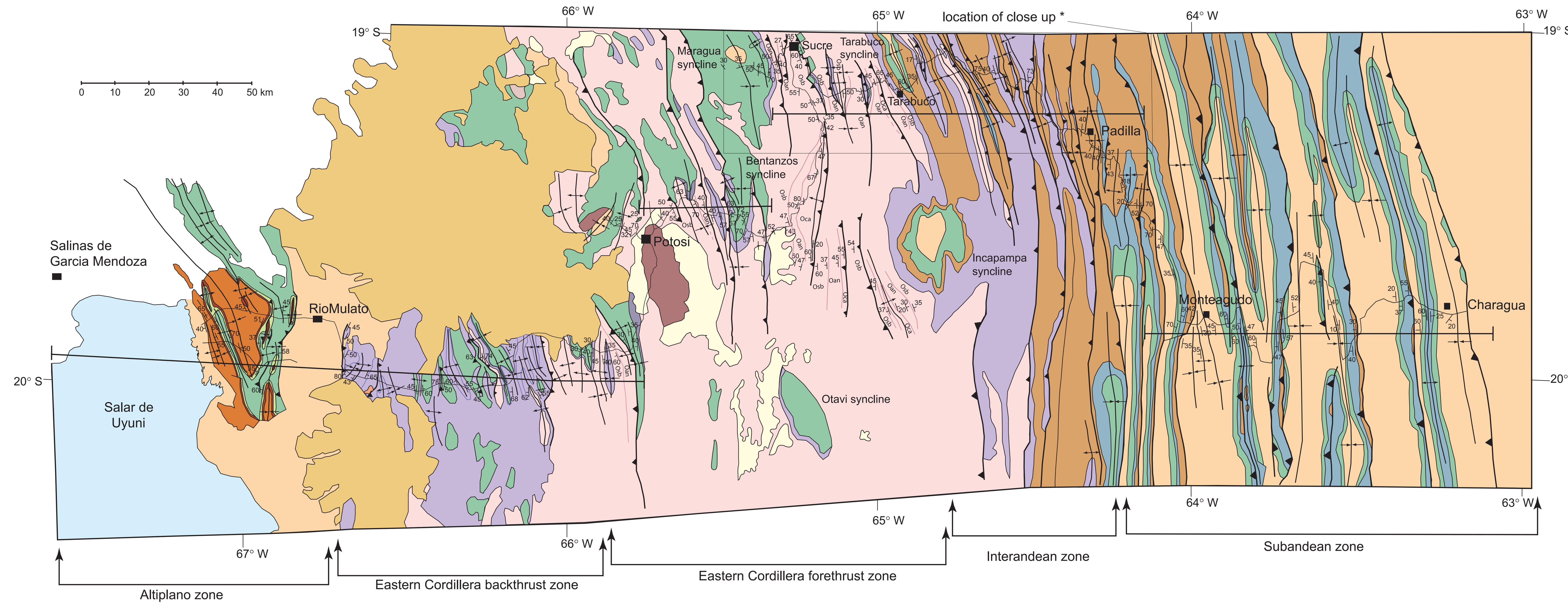
Figure 4 Southern cross section



Index map for Figure 4







1. Thickness of foredeep and slope of basement (top of Siluruan) determined from industry seismic reflection lines and well data (Dunn et al., 1995; Baby et al., 1995).
2. The thickness of the Silurian and Ordovician rocks is unknown. The presence of Ordovician rocks in the foreland was suggested by paleogeographic maps (Sempere, 1995). The thickness of the Silurian is based on thicknesses of Silurian rocks exposed in the Interandean zone. Both Ordovician and Silurian rocks are inferred to thin toward the foreland.
3. Duplexing of upper Devonian rocks is proposed to explain tight anticline (similar to structures imaged on seismic reflection lines and drilled by wells in the Sararenda and Charagua anticlines). Bed length projected into the air equals the bed length of horses within the duplex.
4. Eastward limit of basement thrusting based on seismic refraction (Wigger et al., 1994; Dunn et al., 1995), magnetotelluric and gravity data (Kley et al., 1996). Dip of basement decollement increases to 4°.
5. Long length of Silurian through upper Devonian thrust sheet is based on mapped Silurian Catavi Formation and Devonian Vila Vila Formation syncline overlying Devonian Icla Formation. Bedding orientations in hanging wall and footwall rocks are conformable suggesting a hanging wall flat on footwall flat relationship.
6. Rapid increase in thickness of Ordovician rocks is proposed due to thick sections of Ordovician rocks mapped in the Eastern Cordillera and reasonable thicknesses inferred for Ordovician rocks within the Interandean zone.
7. Increase in structural elevation and need for upper basement thrust based on uniformly dipping (eastward) section of Cretaceous through lower Ordovician rocks. The structural high is the result of an overlap between a hangingwall ramp (upper basement thrust) and the top of a footwall ramp (lower basement thrust).
8. Base of footwall ramp marked by Maragua syncline.
9. Area of angular unconformity (local) between lower Silurian and Jurassic rocks.
10. Location of basement ramp placed at the western most outcrop of Paleozoic rocks (McQuarrie and DeCelles, 2001).
11. Geometry and depth of basin confirmed by industry seismic lines.
12. Depth to Jurassic/Cretaceous detachment based on thickness and dip of Tertiary rocks exposed on western limb of anticline.
13. Geometry, location and depth of salt-cored fault-propagation anticline based on industry seismic reflection data.
14. Location of basement high and geometry of duplex projected from northern cross-section.
15. East-dipping (and eastward diverging?) Tertiary rocks from industry seismic reflection data.

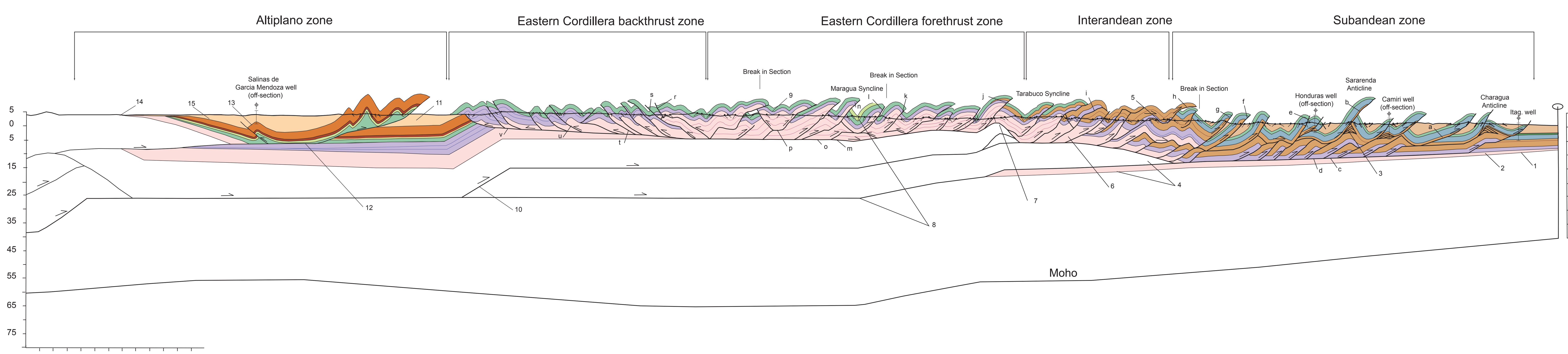


Figure 4
Southern cross-section, restored section and generalized geologic map for the southern cross-section. The map is simplified from Pareja et al. (1978), and Geobol (1962a; 1962b; 1962c; 1962d; 1996b), with detailed mapping along specified transects superimposed. Major tectono-structural zones identified by brackets. Numbers refer to annotations on left side of plate. Ocp, Oan, and Osb refer to Ordovician Capinota, Anzaldo and San Benito Formations respectively.