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Geometry and structural evolution of the central Andean backthrust belt, Bolivia

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Abstract. The central Andean backthrust belt is a large-scale west vergent thrust system along the western side of the Eastern Cordillera in the generally east vergent Andean fold-thrust belt of Bolivia. Although west vergent structures in the central Andes have been recognized previously, we describe the backthrust belt at a regional scale, emphasizing its implications for the kinematic development of the Andes and the subsequent influence of these kinematics on amounts of tectonic shortening. We use techniques such as line length balancing, restorability, and the viability of the progressive development of the structures to construct balanced cross sections across the backthrust belt and Altiplano. The cross sections are taken to a regional depth of detachment (basement) to examine the relationship between mapped surface structures and inferred subsurface structures. The relationship of the backthrust belt to the Altiplano suggests that the Altiplano basin is a crustal-scale piggyback basin created as a basement megathrust propagated up and over a half-crustal scale ramp located just west of the physiographic boundary of the Eastern Cordillera. This basement megathrust was the means by which a narrow Paleocene fold-thrust belt located to the west of the Altiplano propagated eastward and emerged in the present Eastern Cordillera. The relationship between the basement thrusts and the physiographic boundaries of the Central Andean plateau (as defined by *Isacks* [1988]) suggests that extensive megathrust sheets (involving crystalline basement or quartzite) may play an important role in the formation of orogenic plateaus. The kinematic development of the Andean fold-thrust belt indicates that the backthrust belt developed as a taper-building mechanism after the basement megathrust overextended the system eastward. The mechanism proposed in this study for the development of the central Andean backthrust belt requires a minimum of 200 km of shortening within the Altiplano/Eastern Cordillera alone. This increases minimum shortening estimates across the fold-thrust belt in Bolivia to as much as 300-340 km.

1. Introduction

The Andean mountain belt extends ~8000 km along the western margin of South America and is the result of compressional strain associated with the subduction of the Nazca Plate. The central Andes in northern Chile, Bolivia, and southern Peru form the widest portion of the mountain belt and contain a 4 km high, 400 km wide orogenic plateau, the eastern side of which continues to be an actively deforming fold-thrust belt. 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; *Sheffels*, 1990; *Schmitz*, 1994; *Lamb and Hoke*, 1997] which may have started as early as late Cretaceous/early Paleocene time [*Coney and Evenchick*, 1994; *Sempere*, 1995; *Sempere et al.*, 1997; *Horton and DeCelles*, 1997; *Horton et al.*, 2001]. Existing estimates of shortening [*Sheffels*, 1990; *Lamb and Hoke*, 1997; *Kley and Monaldi*, 1998] do not account for the 60-70 km thick crust of the Andean plateau [*Wigger et al.*, 1994; *Zandt et al.*, 1994; *Beck et al.*, 1996, *Swenson et al.*, 2000]. However, these estimates typically consider only the eastern half of the Andes, which consists of the Eastern Cordillera and sub-Andean portions of the fold-thrust belt [*Kley and Monaldi*, 1998]. The causes and mechanisms of crustal shortening, and hence thickening, in the Bolivian Andes are poorly understood, in part, because the geology of the hinterland of the fold-thrust belt is not well known.

This paper focuses on the geometry and structural evolution of a regional hinterland backthrust system that extends along the western flank of the Eastern Cordillera (Figure 1). This backthrust system extends for ~600 km along strike from the Eastern Cordillera, northeast of Lake Titicaca, to the highlands of the Eastern Cordillera southeast of the Salar de Uyuni, and ~150 km across strike from the middle of the Eastern Cordillera to ~70 km into the Altiplano proper (Figure 2). The predominant vergence of the faults and folds in this area is toward the west, and the faults generally step up section into younger rocks from east to west. The westward vergence of structures in this area is used to define the geographical boundaries of the backthrust system. The backthrust belt connects the kinematic development of the Altiplano with the eastward propagating portion of the Andean fold-thrust belt. Although several papers have reported westward verging features in the Eastern Cordillera [*Roeder*, 1988; *Sempere et al.*, 1990; *Baby et al.*, 1990; *Roeder and Chamberlain*, 1995; *Baby et al.*, 1997], the published cross sections are schematic and thus do not provide the detail necessary to understand the geometry of the central Andean backthrust belt, its lateral variations, and its kinematic connection to the eastward propagating portions of the fold-thrust belt.

This paper presents three balanced cross sections in northern, central, and southern Bolivia, constructed using modern concepts of thrusting [*Dahlstrom*, 1970; *Boyer and Elliott*, 1982]. These cross sections allow us to address the geometrical relationship between the Altiplano and the central Andean backthrust belt, specifically the temporal and spatial relationships between thrusts and the geometry of subsurface structures. Unique features described in this paper, and illustrated in the cross sections, such as backthrusts, basement offsets, basement megathrusts, and a crustal-scale piggyback basin, suggest a specific kinematic

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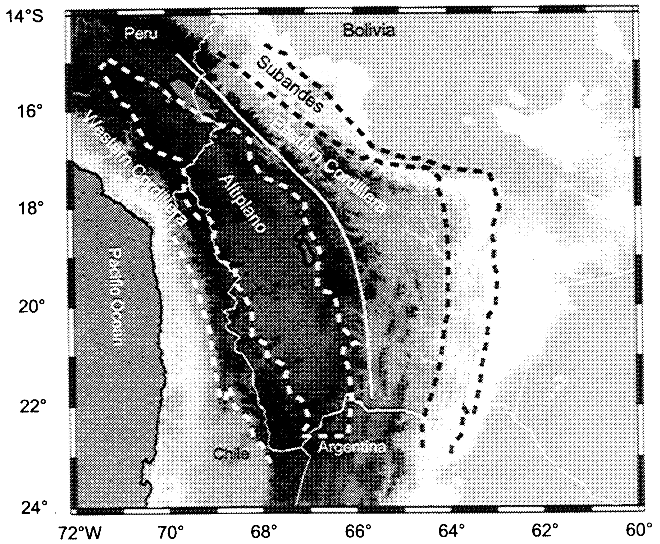

Figure 1. Topography of the central Andes with major physiograhic divisions. White line within the Eastern Cordillera represents the approximate eastern edge of the Central Andean backthrust belt.

development for the central Andean fold-thrust belt and the central Andean plateau and increase the minimum amount of tectonic shortening accommodated by the Andean fold-thrust belt in this region.

2. Geologic Background

The central Andes fold-thrust belt is subdivided into four physiographically distinct provinces: the Western Cordillera, Altiplano, Eastern Cordillera, and the sub-Andean zone (Figure 1). The central Andean plateau is defined as the region with average elevations >3 km [*Isacks*, 1988; *Gubbels* et al., 1993; *Masek* et al., 1994; *Lamb and Hoke*, 1997] and contains three of these physiographically different provinces. The Western Cordillera is the active volcanic arc straddling the international border between Bolivia and Chile. It rises ~2 km above the surrounding plateau with the high peaks reaching >6 km. The Altiplano is a wide (200 km) internally drained region of subdued topography east of the Western Cordillera. It has been an isolated basin from the late Miocene to present [*Vandervoort et al.*, 1995], and some authors have proposed that it has existed as a distinct basin since the latest Cretaceous [*Lamb and Hoke*, 1997]. Locally narrow mountain ranges consisting of folded Cretaceous to Tertiary shale, sandstone, and conglomerate rise

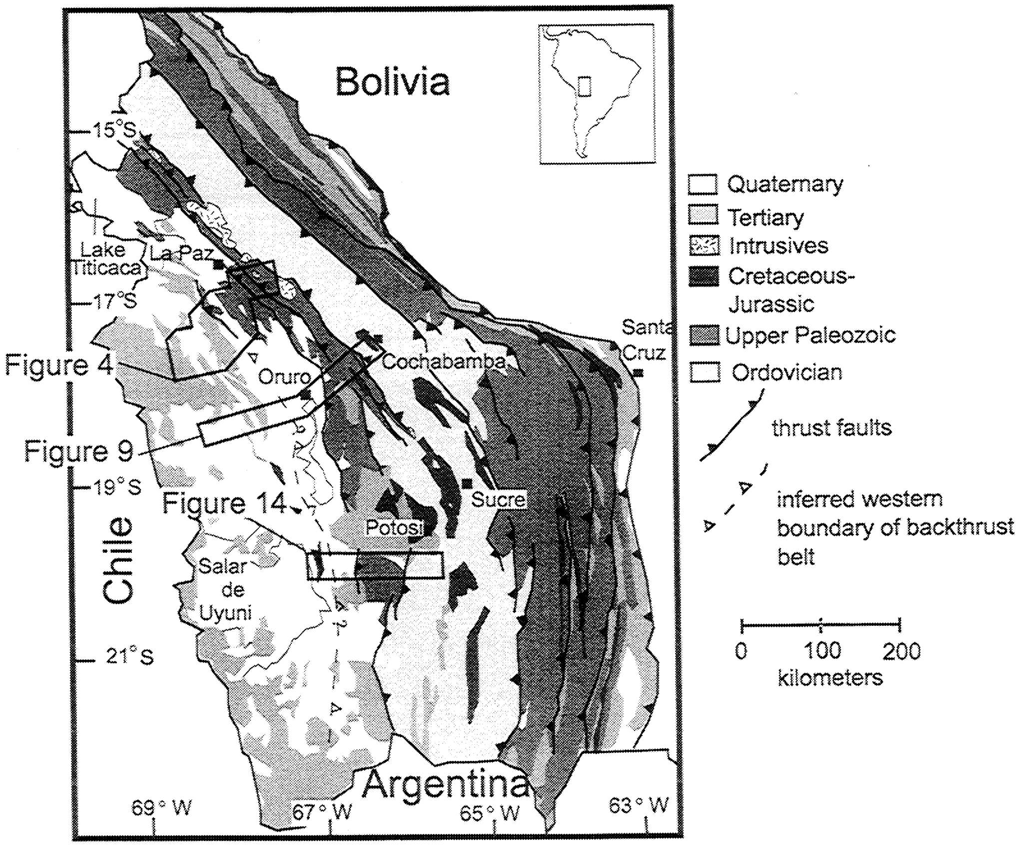

Figure 2. Generalized geologic map of Bolivia (simplified from *Pareja et al.* [1978]) illustrating major lithologic boundaries, thrust systems, and locations of cross sections. Boxes are locations of Figures 4, 9, and 14. Geographic extent of the Central Andean backthrust belt is indicated by the thrust faults with barbs on the east side.

~1 km above the ~3.8 km high floor of the Altiplano basin. The third province, the Eastern Cordillera, rises abruptly from the Altiplano to elevations as high as 6.4 km. It is a bivergent (eastward and westward) fold–thrust belt composed of Paleozoic, Mesozoic, and Tertiary rocks. On the eastern side of the Eastern Cordillera, the elevation of the plateau decreases toward the modern, sub-Andean fold-thrust belt. The sub-Andean zone is the most tectonically active part of the Andean orogen [*Dunn et al.*, 1995; *Moretti et al.*, 1996] accommodating ~10-15 mm/yr of the ~80 mm/yr convergence of the Nazca and the South American Plates [*Norabuena et al.*, 1998].

3. Balanced Cross Sections

Although cross sections have been constructed from the Altiplano to the high peaks of the Eastern Cordillera [*Roeder* 1988; *Baby et al.*, 1997; *Kley et al.*, 1997; *Lamb and Hoke*, 1997; *Rochat et al.*, 1999], the published cross sections are either schematic or the methods employed do not extend the sections to a regional detachment and require balance. In this study, we constructed three cross sections from the Altiplano through the Eastern Cordillera using line length balancing while paying particular attention to restorability and the viability of the progressive development of the structures. Each section extends from the Altiplano to the high peaks of the Eastern Cordillera in the northern (Huarina A), central (Lago Poopo B), and southern (Rio Mulato-Kilpani C) sectors of the central Andean backthrust belt (Figure 2). The cross sections are based on mapped transects roughly coincident with the lines of section (see Figures 4, 9, and 14). The new mapping at a scale of 1:50,000 and 1:100,000 and the field-checked regional maps (1:100,000 and 1;250,000) were compiled on 1:100,000 scale topographic maps across the study areas. Seismic reflection and well-hole data (courtesy of Yacimiento Petroliferos Fiscales Bolivianos (YPFB)) were used to constrain the geometries of covered structures on the western and eastern edges of the Altiplano in the central and southern cross sections. Each of the cross sections provides different levels of exposure into the fold-thrust belt and takes advantage of the best exposures across the transition between the Eastern Cordillera and the Altiplano. Relationships exposed and documented well in one section are extrapolated and used as a template for the style of deformation within the covered and less exposed regions of the other cross sections. The relationships depicted in these cross sections may be viewed as a window into the style of deformation buried under much of the Quaternary cover of the Altiplano. The cross sections are taken to a regional depth of detachment (basement), forcing careful consideration of the relationship between mapped surface structures and inferred subsurface structures. Constructing the cross sections in this way allows for significant predictions about the kinematic and geometric development of the Andean fold-thrust belt as a whole.

3.1. Northern Cross Section (Huarina Fold-Thrust Belt)

3.1.1. Stratigraphy. The strata involved in the northern cross section range in age from Ordovician slates, phyllites, and quartzites, to upper Tertiary synorogenic sediments. The strati-

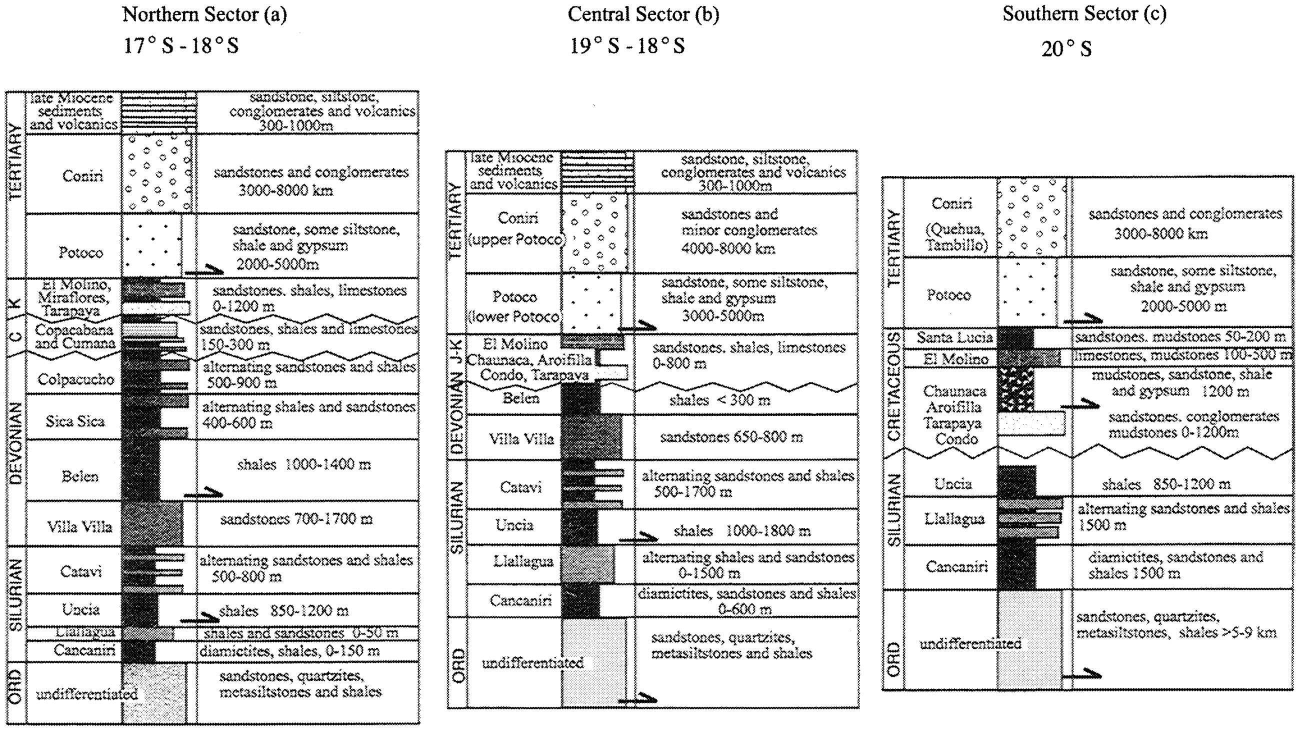

Figure 3. Stratigraphic columns for the (a) northern, (b) central, and (c) southern sectors of the backthrust belt. Descriptions and thicknesses are from *Sempere* [1995], *Suarez-Soruco* [1995], *Gagnier et al.*, [1996], *González et al.* [1996], *Lamb and Hoke* [1997], *Horton et al.* [2001], and this study. Arrows represent detachment horizons; zigzag line represents large unconformities.

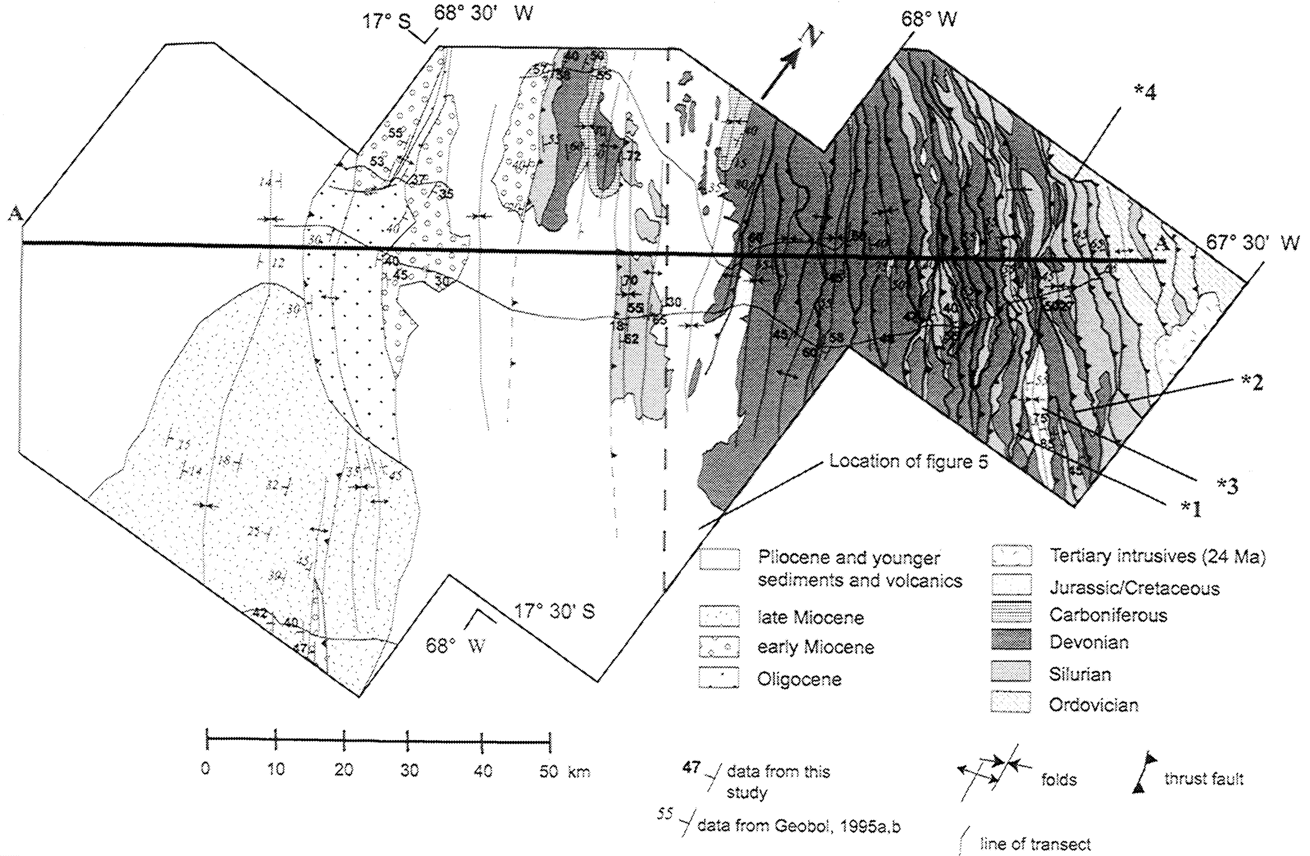

Figure 4. Generalized geologic map of the northern sector of the central Andean backthrust belt, the Corque syncline and Huarina region (simplified from *GEOBOL* [1967, 1995a, 1995b, 1996a] and our own mapping). Starred numbers refer to locations discussed in the text.

graphy is described here in terms of mappable units, with emphasis on mechanical stratigraphy (Figure 3).

The main detachment horizon for the Huarina fold-thrust belt is at the base of the Silurian Uncia Formation. The Uncia Formation is an 850-1200 m thick unit of shale and siltstone [*González et al.*, 1996]. The Uncia is generally the oldest unit exposed in the backthrust belt, except in the easternmost exposures where the structures occur primarily within the quartzite and siltite of the Ordovician. The thrust sheets, which detach in the Uncia Formation, carry the Silurian Catavi and the Devonian Vila Vila Formations. The Catavi Formation is a 500-800 m thick unit of alternating shale and thin-bedded quartzose sandstone [*González et al.*, 1996]. The alternating sandstone and shale accommodate locally significant internal deformation, mesoscale folds, differential thickening and thinning, and secondary detachment levels. The Vila Vila Formation (700-1700 m) is composed of thick-bedded (1-3 m) sandstone, quartzite, and minor shale and is the most structurally competent unit. The next main detachment horizon is in the Belén Formation. The Belén Formation is 1000-1400 m thick and composed of shale and thin-bedded sandstone [*González et al.*, 1996]. A detachment horizon in the Belén Formation is needed to balance shortening within eroded upper Devonian rocks with the shortening exhibited by the Silurian imbricate fan (Figure 6).

The upper Devonian units, i.e., the Sica Sica Formation (400-600 m) and the Colpacucho Formation (500-900 m), both contain alternating sandstone and siltstone beds [*González et al.*, 1996]. The Carboniferous units, i.e., the Cumana and Copacabana Formations, consist of 15-300 m of sandstone, siltstone, and limestone [*González et al.*, 1996] and are only locally present within the study area. The eastern edge of the Altiplano is the site of a pre-Carboniferous erosional unconformity [*Sempere*, 1995] that juxtaposes Carboniferous on upper Devonian (in the east) and Carboniferous rocks on lower Devonian (in the west).

The Cretaceous units, i.e., the Tarapaya, Miraflores, and El Molino Formations, are exposed where preserved from erosion in narrow fault bounded synclines within the Huarina sector of the backthrust belt and in local outcrops west of the Corque syncline. Because of their exposure to the west and east of the syncline these Cretaceous units are most likely present underneath the thick sedimentary fill of the Corque syncline. The 50-200 m thick Paleocene Santa Lucia Formation consists of sandstone and mudstone and overlies Cretaceous rocks both in the narrow fault-bounded synclines and also in the western part of the Altiplano [*Sempere et al.*, 1997; *Horton et al.*, 2001]. The Santa Lucia Formation is overlain by a 2-6 km thick succession of sandstone, mudstone, and limited evaporites [*Horton et al.*, 2001]. The evaporites are mostly concentrated in the lower part of the section and provide detachment horizons that accommodate folding and faulting within the syncline.

Due west of the Huarina sector, and probably closely connected with its development, are crustal-scale (~10 km amplitude) synclines (Corque and Topohoco synclines) in Tertiary strata [*Rochat et al.*, 1996; *Lamb and Hoke,* 1997; *Baby et al.*, 1997; *Rochat et al.*, 1999]. The formations involved in the synclines (as exposed on the surface) are late Eocene/ early Oligocene and younger nonmarine sedimentary rocks that were deposited in part in a foreland basin system associated with the developing Andean fold-thrust belt to the west [*Sempere*, 1995; *Horton and DeCelles,* 1997; *Horton et al.*, 2001]. Despite uniform lithologic characteristics over a broad area, the nomenclature for the Oligocene-early Miocene stratigraphic interval varies along strike. However, it is most commonly known as the Potoco Formation or Potoco equivalents and can be as thick as 5 km [*Lamb and Hoke,* 1997; *Horton et al.*, 2001]. A 3-8 km thick section containing both sedimentary and volcanic rocks overlies the Potoco Formation. The lower part of this succession contains early to mid-Miocene sandstone and conglomerate derived from both the west and the east [*Lamb and Hoke,* 1997; *Hampton and Horton*, 2000]. Within the eastern limb of the Topohoco syncline, these younger deposits are distinguished by the presence of growth structures related to the westward propagation of the backthrust belt [*Sempere et al.*, 1990; *Lamb and Hoke,* 1997]. In the eastern limb of the Corque syncline the early to mid-Miocene rocks are overlain in angular unconformity by younger (<9 Ma) synorogenic sedimentary rocks [*Lamb and Hoke*, 1997].

3.1.2. Structure. The northern sector of the Central Andean backthrust belt is a westward verging thrust system referred to as the Huarina fold-thrust belt [*Sempere et al.*, 1990]. The oldest rocks and deepest structures are exposed in the east with progressively younger rocks and shallower levels of deformation to the west. The style of deformation within the belt is a series of fault propagation folds and imbricate fans, with the amount of displacement generally decreasing to the west. The major structural features include a 12 km high basement step marked by the eastern limb of the Topohoco syncline, a fault propagation fold belt in upper Devonian rocks at the surface, an imbricate belt in lower Devonian and Silurian rocks, and duplexes within the Silurian rocks (Figures 4, 5, and 6). The Silurian Uncia Formation was chosen as the main detachment horizon for the

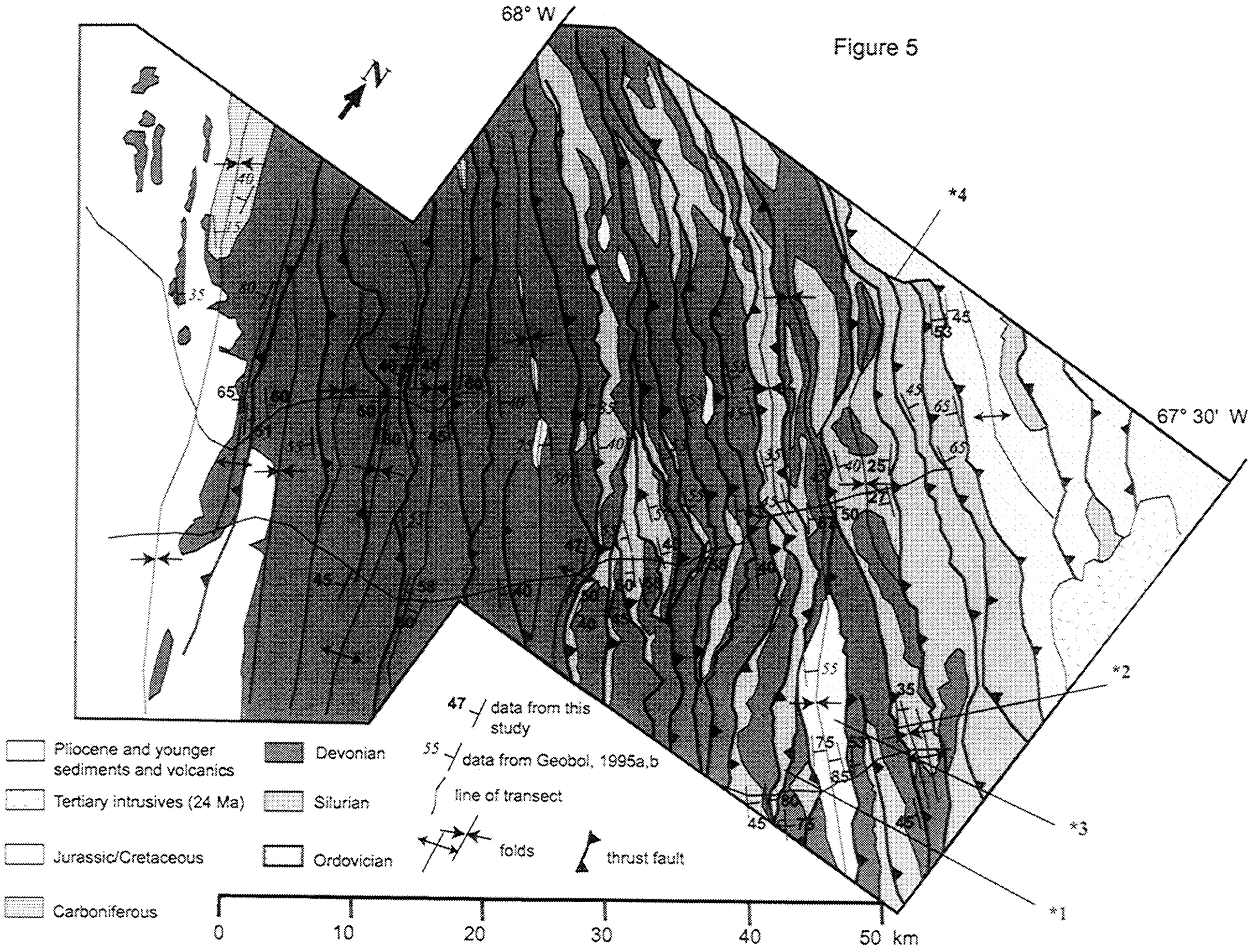

Figure 5. The northern sector of the central Andean backthrust belt. The backthrust portion of Figure 4 is enlarged to show field data and structural complexities. Starred numbers refer to locations discussed in the text.

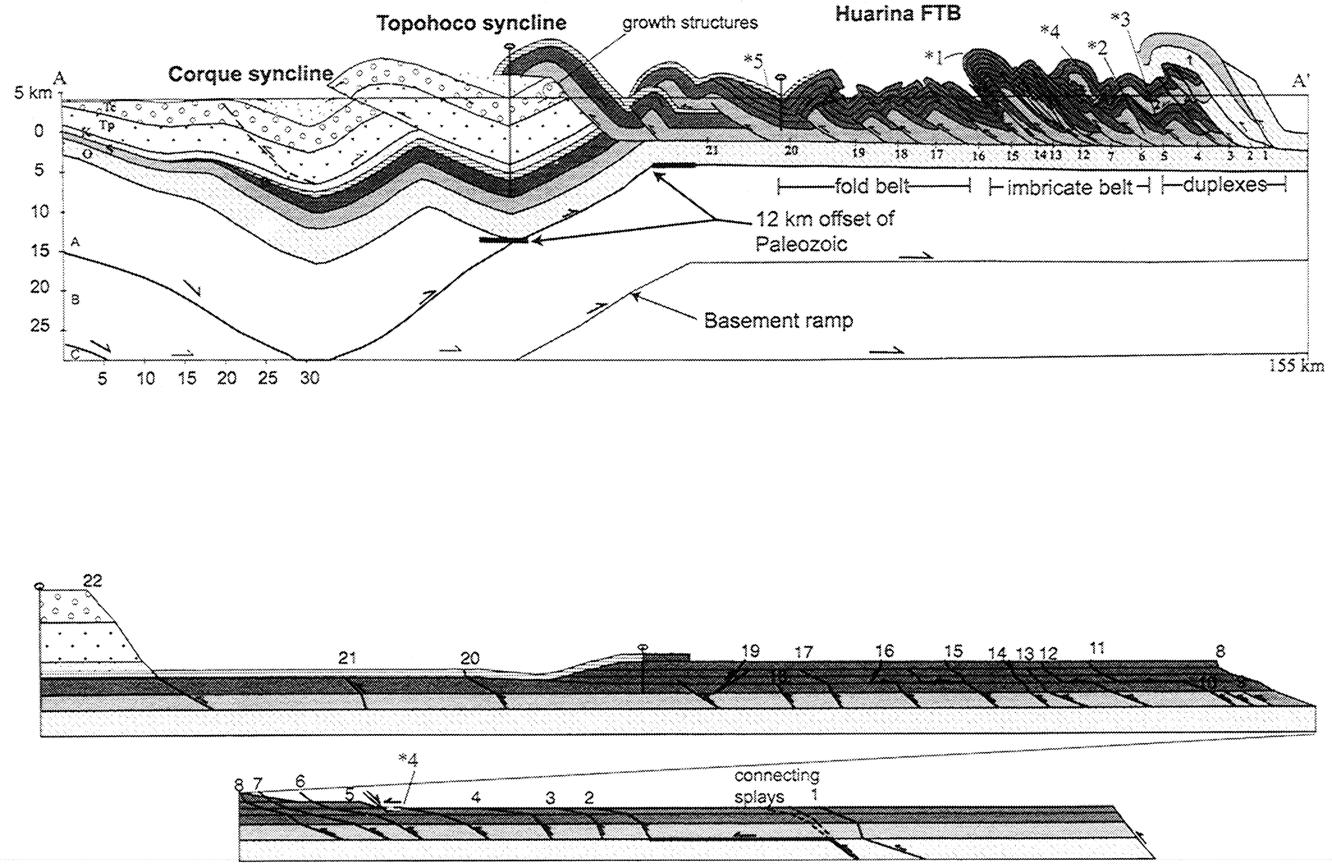

Figure 6. Balanced cross section and restored section for the northern sector of the backthrust belt. See Figures 2 and 4 for location and Figure 3 for key to stratigraphic formation names. Starred numbers identify points discussed in text, and numbered thrusts refer to sequence of thrusting. Upper line between A and A' represents the modern topographic surface. The full geometry of basement thrusts A, B, and C can be seen in the composite cross section in Figure 18a.

northern sector because it is the oldest unit consistently exposed in the hanging wall of major thrusts and lesser imbricates throughout this sector of the backthrust belt.

3.1.2.1. Basement offset: The 10+ km thick section of synorogenic sediments preserved in the Corque and Topohoco synclines constrains the minimum depth to basement at a depth of 15 km. Two options for the depth to basement under the northern sector of the backthrust belt include a similar depth to basement of 15 km, or a minimum depth to basement of 3 km below sea level, which is simply the total thickness of the preserved Paleozoic section. Choosing the conservative option, and proposing a basal detachment in the Silurian Uncia Formation below which there is no duplication of the Paleozoic section, results in an ~12 km vertical offset of the basement cover interface between the eastern and western parts of the northern sector (Figure 6). The thrust contact between the folded synorogenic sediments and the Paleozoic rocks suggests that the basement offset and associated broad folding of the Paleozoic through early Tertiary rocks predate the westward propagation of the backthrust belt into this area.

3.1.2.2. Fold belt: The Devonian fold belt in the central part of the cross section is flanked on both sides by major thrusts that carry the Silurian Uncia Formation. Thus we interpret the Devonian fold belt as a set of fault propagation folds initiating at the Uncia detachment horizon. The offsets on these thrusts diminish up section, and shortening is taken up in folding and small-offset faulting within the upper Devonian units. The faults verge both to the west and east and are interpreted in several instances to sole out in the Devonian Belén Formation.

3.1.2.3. Imbricate belt: Toward the east, the structures are more closely spaced than their counterparts to the west, creating an imbricate fan in the Silurian and lower Devonian formations. The imbricate belt resembles a complicated, large, antiform-synform pair (Figures 5 and 6, *1). The synform is cored by Cretaceous rocks in the middle of the cross section. The associated antiform is cored by an imbricate fan within Silurian rocks. Although no longer present, the upper Devonian rocks had to accommodate similar amounts of shortening as the rocks preserved in the imbricate fan. The excess Devonian rocks were probably eroded as fast as they were uplifted, indicating the structure (as it is drawn) might never have existed. However, the shortening of the upper Devonian units must equal that in the lower Devonian-Silurian units.

3.1.2.4. Roof thrusts: The duplexes drawn in the cross section are recognized by map patterns and branching thrust faults, which suggests the presence of roof thrusts. Evidence for a Silu-

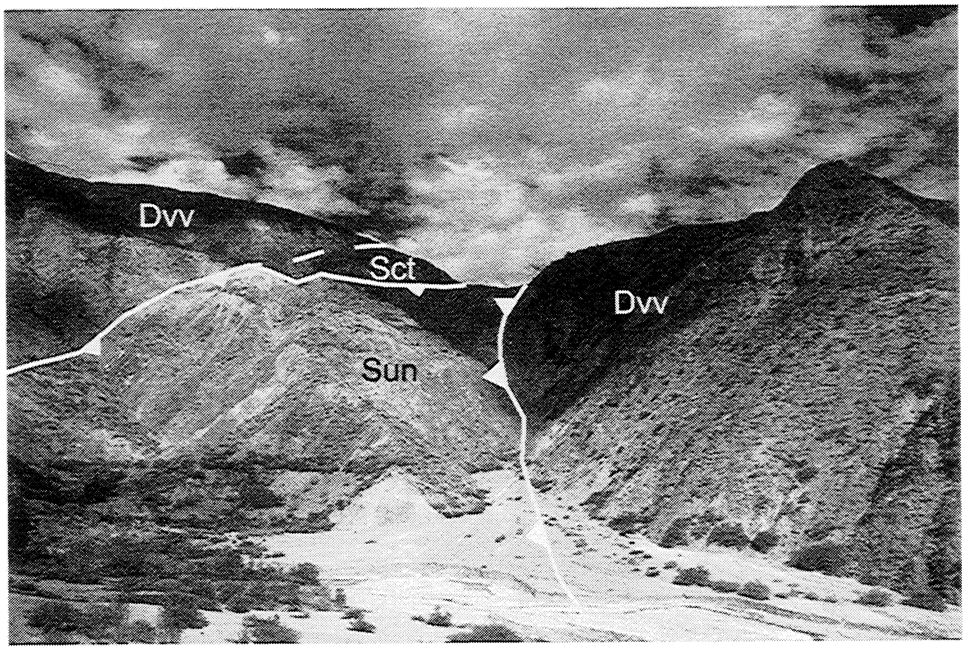

Figure 7. Photograph of Silurian roof sheet looking east. Location is indicated by *1 on Figures 4 and 5. Dvv is the Devonian Vila Vila Formation, Sct is the Silurian Catavi Formation, and Sun is the Silurian Uncia Formation.

rian roof thrust (Figure 6, thrust 2) includes the slice of lower Silurian Uncia Formation bounded by west and east dipping faults in the SE corner of the map (Figures 4 and 5, *1, Figure 7). These two faults join to the southeast, suggesting they are the same fault. Both faults are traceable along strike over much of the Sapahaqui 1:100,000 map [*Servicio Geológico de Bolivia (GEOBOL)*, 1995b], implying that the fault is extensive. The amount of stratigraphic separation on both the east and west dipping faults is incompatible with a simple two-fault interpretation. The faults would intersect in the subsurface before they reach the Uncia Formation. We interpret this fault-bounded syncline as a Silurian thrust sheet that has been folded by duplexing of underlying units (Figure 6, * 2). This sheet must root in the thrust belt east of its present location (Figure 6, *3). We propose that the next significant Silurian thrust to the east (Figures 4 and 5, *2) is the eastern continuation of the same fault. Between these two Silurian thrusts is a large, Cretaceous-cored syncline (Figures 4 and 5, *3). For the above interpretation to be correct, the pocket of Cretaceous and younger rocks must have been downfaulted before it was overthrust by the Silurian thrust sheet. The apparent downcutting of the Silurian roof thrust from the Devonian Belén Formation to the Devonian Vila Vila Formation suggests that significant Cretaceous paleorelief existed in this part of the section. The "missing" Belén is dashed-in on the restored section (Figure 6, fault 5) and a local, pre-Andean normal fault provides the accommodation space for the Cretaceous rocks (Figure 6, *4). Evidence for local Cretaceous extension in the Eastern Cordillera is abundant [*Sempere*, 1995].

Ordovician rocks are exposed only at the eastern edge of the Huarina sector (Figure 6, thrust 1). In the northeast corner of the Saphiqui map (Figures 4 and 5, *4), three thrusts that carry Silurian rocks join a larger thrust that carries Ordovician rocks. This branching pattern of thrusts suggests that the Ordovician rocks are carried by a large roof thrust (Figure 6, fault 1) above a duplex in Silurian rocks. The geometry of this duplex can be envisioned in down plunge view to the north-northwest. Very little stratigraphic separation exists between the Silurian roof thrust (fault 2) and this duplex directly to the east. We propose that the Silurian thrust sheet (fault 2) is cut by these minor faults that join the Ordovician thrust, making this part of the structure a connecting splay duplex [*Mitra and Sussman*, 1997]. The connecting splay duplex transferred motion from the floor thrust of the lower duplex through the Silurian roof sheet to the structurally higher Ordovician roof thrust. This sequence is schematically illustrated in Figure 8. One or two additional Ordovician thrust sheets are present to the northeast before the system becomes predominantly east verging.

3.1.3. Balance. The backthrust belt was line length balanced from the axis of the Topohoco syncline to the westernmost thrust in Ordovician rocks (thrust 1) (Figure 6). This was achieved by assuming that the cross section is "pinned" at the axial surface of the Topohoco syncline, measuring the lengths of the top and bottom of each formation to the next fault and matching the hanging wall and footwall cutoff lengths on the restored section with those on the cross section. Because the upper Devonian rocks are not present in the western part of the cross section, another “pin” was used in the first large syncline that includes the complete upper Devonian section (Figure 6, *5). The upper Devonian rocks are included in the cross section and restored section where the along-strike map patterns suggest they were present during deformation. The large Jurassic-and Cretaceous-cored syncline in the SE corner of the Sapahaqui map rests on the lower Devonian Belén Formation, suggesting that by Jurassic time the upper Devonian Sica Sica and Colpacucho Formations had been removed by erosion (Figures 4 and 5, *3). Many of the thrusts shown on the restored section are steep (45°-60°) and are

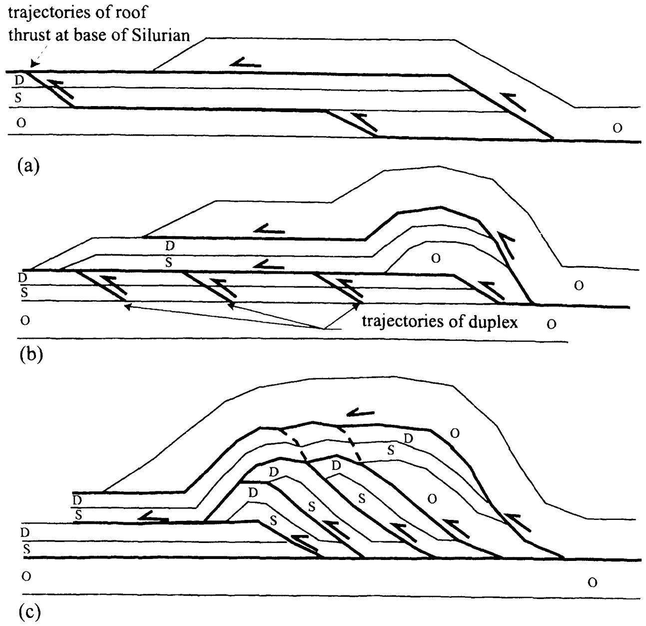

Figure 8. Sequence diagram (not to scale) showing progressive development of the postulated connecting splay duplex [*Mitra and Sussman*, 1997] in the eastern part of the Huarina sector. (a) Emplacement of Ordovician roof sheet. Lower thrust represents trajectory of the Silurian roof thrust (discussed in text). (b) Emplacement of the Silurian sheet shown with the trajectories of the future duplex faults. (c) Formation of the Silurian duplex. Most of the slip on the internal faults is fed to the Silurian roof sheet. The final motion on each horse, however, is transferred through the Silurian sheet into the Ordovician roof thrust creating a connecting splay duplex. Connecting splays are shown with dashed lines.

interpreted to be a result of the development of fault propagation folds. Shortening estimates for the backthrust belt and the entire northern sector are listed in Table 1. We emphasize that these are minimum estimates because small-scale deformation and microstrain were not incorporated.

3.2. Central Cross Section (Lago Poopo Sector)

3.2.1. Stratigraphy. The central sector of the backthrust belt involves similar stratigraphy as that exposed farther north. The rocks involved in the deformation range from Ordovician marine siliciclastic rocks to upper Tertiary synorogenic sediments. The level of post-Andean erosion is slightly less than to the north, leaving Jurassic and Cretaceous rocks exposed in many of the elongate northwest-southeast synclines in the area (Figures 9 and 10). The stratigraphic section for the central sector is shown in Figure 3.

The main detachment horizon for the Lago Poopo sector of the backthrust belt is at the base of and within Ordovician sandstone, shale, slate, and quartzite. The complete stratigraphic thickness of Ordovician rocks in this area is unknown; however, the thickness of exposed Ordovician ranges from 5 to 7 km [*Rivas,* 1971; *Rodrigo-Gainza and Castaños*, 1978]. The exposed Ordovician can be divided into three distinct units: the Capinota, Anzaldo, and San Benito Formations. The Capinota Formation contains dark siltite, phyllite, and slate. It is a mechanically weak layer, and both the top and bottom of this unit are interpreted to be major detachment horizons for this portion of the backthrust belt. The Capinota is overlain by the mechanically strong siltite and quartzite of the Anzaldo Formation. The thick-bedded quartzite of the San Benito Formation is the mechanically strongest layer within the Ordovician sequence. The Ordovician rocks consist of thick, marine sequences of shallowing upward sandstone and shale that are conformably overlain by the Cancañiri Formation [*Sempere,* 1995; *Sempere et al.*, 1991; *Baby et al.*, 1992]. The Cancañiri Formation contains glacial-marine diamictite and sandy mudstone that obtain a thickness of 600 m in the area. The Cancañiri is overlain by the Llallagua Formation, a resistant, < 1500 m thick unit of fine-grained sandstone and quartzite with subordinate mudstone. The Cancañiri and Llallagua Formations decrease in thickness both to the east and west. The westward taper is assumed to be depositional [*Gagnier et al.*, 1996, *Suarez-Soruco,* 1995], whereas the eastward taper is most likely erosional. In the central sector of the backthrust belt the Llallagua Formation varies from 1500 m in the west near Lago Poopo to 0 m in the east near Cochabamba (Figures 2 and 3). The Llallagua Formation is overlain by the middle and upper Silurian Uncia and Catavi Formations. The lithologies of both units are similar to those described in the northern sector. Their combined thicknesses range from 1500 m to 3500 m [*González et al.,* 1996]. Most of the Devonian rocks in the central sector are the resistant sandstone and subordinate shale and siltstone of the Vila Vila Formation, which reach thicknesses of 650-800 m [*González et al.*, 1996]. Small amounts (< 350 m) of the Belén Formation are also preserved [*González et al.*, 1996].

The Jurassic and Cretaceous units are preserved in elongate synclines throughout this region of the backthrust belt and are structurally conformable with the underlying Paleozoic rocks (Figures 9 and 10). The Jurassic rocks consist of thick eolianite (the Ravelo Formation) overlain by conglomerate and siltstone of the Condo and Tarapaya Formations. The thickness of these rocks within the central sector is < 300 m. The Cretaceous units are the Aroifilla, Chaunaca and El Molino Formations. These also are thin and discontinuous throughout this sector, reaching maximum thicknesses of < 500 m.

Table 1. Shortening Estimates for the Central Andean Backthrust Belt

Cross Section	Final Length, km	Original Length, km	Shortening, km	Shortening, %
Northern sector (Huarina)	155	296	141	47
Backthrust belt	100	232	132	57
Corque/Topohoco synclines	55	64	9	14
Central sector (Lago Poopo)	286	475	189	40
Backthrust belt	151	293	142	48
Corque/Corocoro syncline	135	182	47	26
Southern sector (Kilpani-Rio Mulato)	125	210	85	40
Backthrust belt	87	130	43	33
Rio Mulato fold belt	38	80	42	52

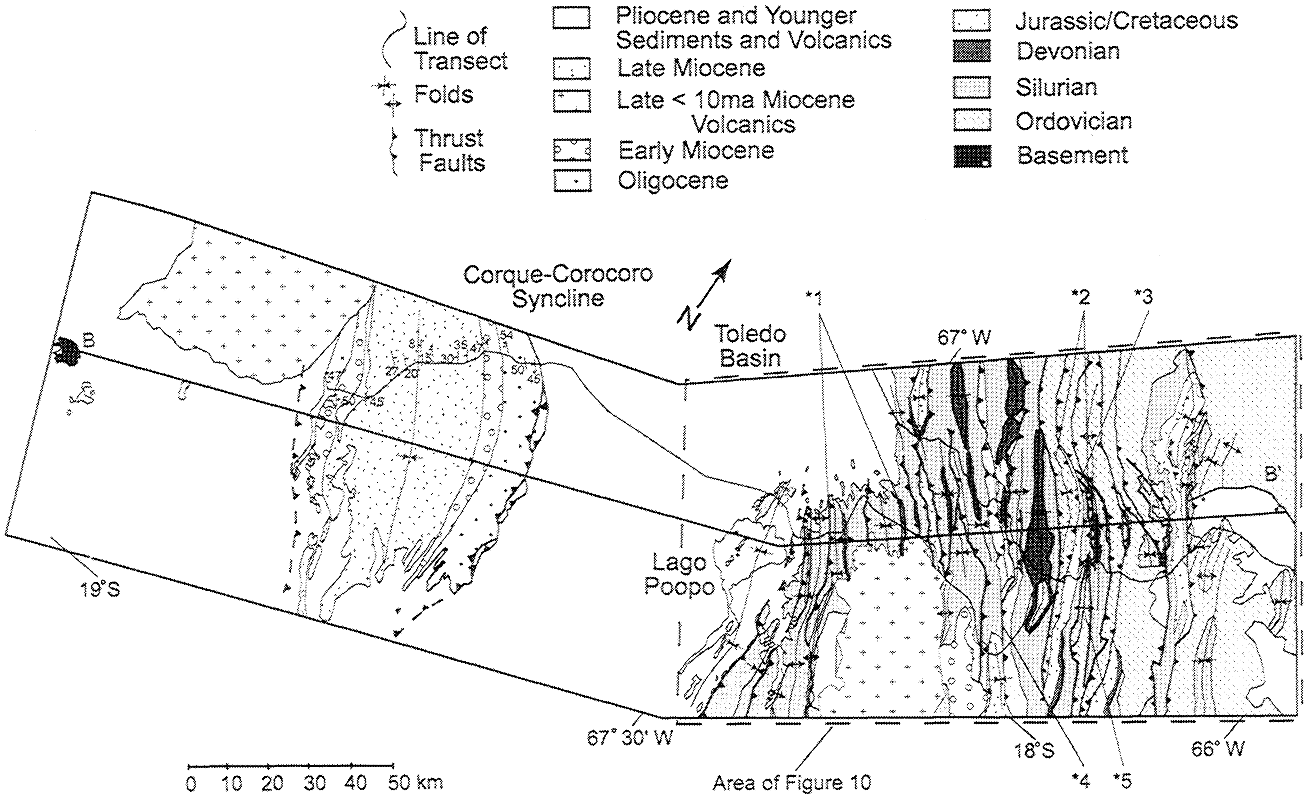

Figure 9. Generalized geologic map of the northern sector of the Central Andean backthrust belt, the Corque syncline, and Lago Poopo region (simplified from *GEOBOL* [1994, 1995c, and 1995d]). Starred numbers refer to locations discussed in the text.

Northwest of Lago Poopo, along the line of section B, is the most well-developed portion of the Corque syncline (Figures 2, 9, and 11). The Tertiary sediments in this part of the syncline reach thicknesses of 15 km. These Tertiary units are the same as those described in the northern sector. However, here the Potoco contains both west (lower 4000 m) and east (upper 3000 m) derived sediments [*Hampton and Horton*, 2000]. The younger Miocene units, thought to record the most rapid phase of sedimentation, were deposited between 25 and 8 Ma and reach thicknesses up to 8 km [*Rochat et al.*, 1996; *Lamb and Hoke*, 1997].

3.2.2. Structure. The structures in the central sector of the backthrust belt can be divided into two main styles, a tightly deformed, west verging backthrust belt in Ordovician through Cretaceous rocks and a broadly deformed, large-amplitude syncline in Tertiary synorogenic sediments (Figure 11). Similar to the northern sector, these two structural regimes are separated by a 12-15 km offset in the level of basement. The main style of deformation within the backthrust belt is a series of fault propagation folds cored by thrusts from the basal detachment. In the Lago Poopo area the complete Silurian section, from the Cancañiri diamictite to the Catavi sandstone, is involved in the tight deformation observed in outcrop exposure. We propose that this deformation is accommodated at depth by faulting within the Ordovician rocks. Thus the basal detachment for the Lago Poopo sector of the backthrust belt is proposed to be at the base of the Ordovician shale.

3.2.2.1 Basement offset: The burial of the Paleozoic section under 15 km of Tertiary sediment within the Corque syncline places the basement/Paleozoic contact at ~20 km depth (Figure 11). In the backthrust belt to the east, however, this same contact is at a depth of ~6 km. This 15 km vertical offset is the same magnitude as the offset described in the northern sector.

3.2.2.2. Subsurface deformation: The deformation drawn east of the Corque syncline and west of the backthrust belt is buried under the young Quaternary cover of the Altiplano. Reflections seismic section interpretation (Figure 12) suggests that faulted and folded Paleozoic rocks extend into this region and that angular unconformities at depth within the Lago Poopo basin (Figures 11 and 12) reflect synsedimentary folding and faulting. Seismic lines and associated well data indicate that under this basin, ~5 km of young (<25 Ma) synorogenic sediments rest on Silurian strata. This suggests that Devonian through Paleocene (and possibly through Oligocene) rocks were removed from this area prior to 25 Ma. The seismic data also suggest an intermediate step in the level of the Paleozoic under the Lago Poopo basin between the level of the Paleozoic exposed in the backthrust belt and the level buried under the Corque syncline directly to the west.

3.2.2.3. Fold belt: The fold belt in the central portion of the cross section is similar in style and location to the Devonian fold belt in the northern sector (Figures 5, 10, and 11). The fold belt contains the entire Silurian section from the Cancañiri Formation to the lower rocks of the Vila Vila Formation. The folds are

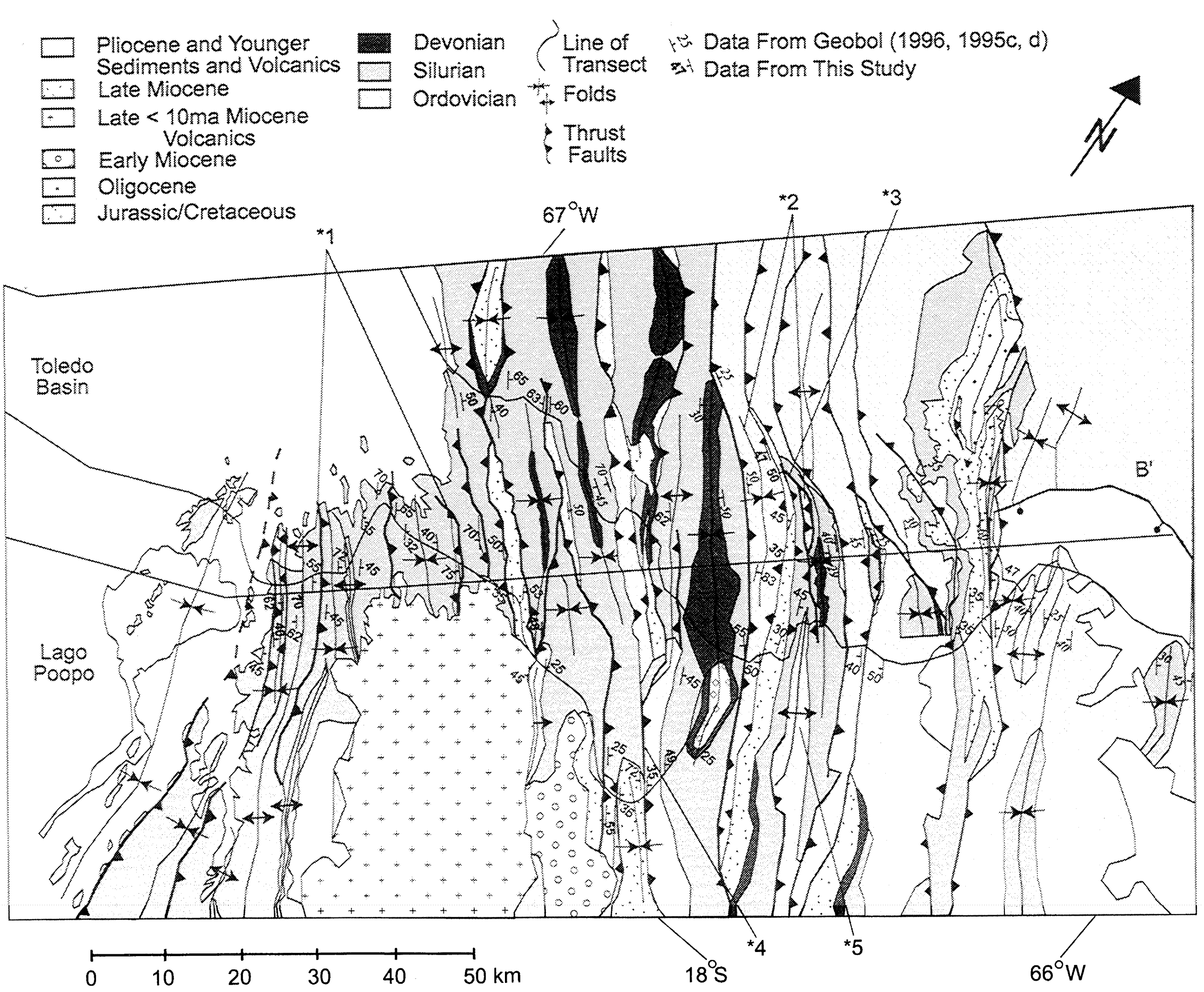

Figure 10. The central sector of the central Andean backthrust belt. The backthrust portion of Figure 9 is enlarged to show field data and structural complexities. Starred numbers refer to locations discussed in the text.

broken by both west and east verging faults at relatively high angles to bedding. (Figure 10, *1). Many of the faults in the fold belt carry the lower Silurian Cancañiri Formation or the upper Ordovician San Benito Formation. We suggest that this fold belt is cored by faults carrying more resistant lower Ordovician sandstone and quartzite and that the structures are fault propagation folds with the faults initiating at the base of or within the Ordovician and transferring displacement into the faults and folds in the Silurian units.

3.2.2.4. Roof thrusts: The duplex drawn in the central cross section is also recognized from map patterns and branching thrust faults (Figures 9 and 10). Fault-bounded Ordovician synclines (Figures 9 and 10, *2), which join to the south, or to the north and south, suggest the presence of an Ordovician roof sheet (Figure 11, *1). These fault systems are traceable along strike over much of the Cochabamba 1:250,000 map [*GEOBOL*, 1995c]. We interpret both of these fault-bounded synclines as the same Ordovician thrust sheet that has been folded by duplexing in underlying Silurian and Ordovician rocks. The evidence for portraying both fault-bounded synclines as the same thrust sheet comes from map patterns to the north (Figures 9 and 10, *3) where the two thrust systems join (Figure 13). We propose that this Ordovician thrust sheet roots down into the subsurface at the next thrust to the east and that the hanging wall cutoff for this thrust sheet is the Ordovician-cored fold and thrust shown in Figure 10, *4. Ordovician rocks carried in the hanging wall of this thrust crop out in several places and the thrust is continuous across the Cochabamba 1:250,000 map [*GEOBOL*, 1995c]. The thrusts labeled *4 and *5 and their relationship to the adjacent Jurassic and Cretaceous rocks suggest that the Silurian/Ordovician over Jurassic/Cretaceous contact (Figures 9 and 10, *5) represents a footwall cutoff in Devonian through Cretaceous rocks (Figure 11, *3 and Figure 13a). The corresponding Devonian-Cretaceous hanging wall cutoff is projected into the air, above the Ordovician-cored fold (Figure 11, *4). The Ordovician roof sheet is broken by an out-of-sequence breakthrough thrust (Figure 11, thrust 7), most likely associated with the formation of duplexes at a lower structural level.

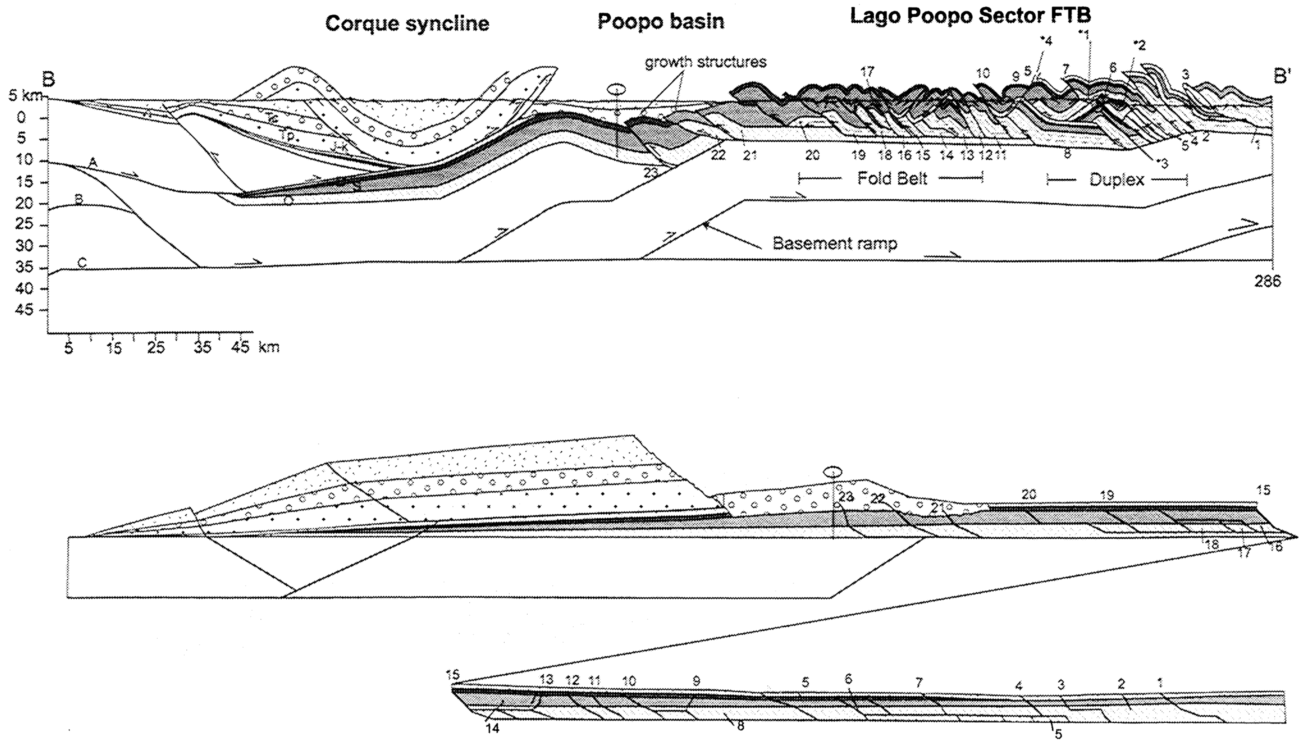

Figure 11. Balanced cross section and restored section for the central sector of the backthrust belt. See Figures 2 and 9 for location and Figure 3 for key to stratigraphic formation names. Starred numbers identify points discussed in text, and numbered thrusts refer to sequence of thrusting. Upper line between B and B' represents the modern topographic surface.

The thrust carrying Ordovician rocks on the easternmost edge of the cross section represents the last major west vergent thrust before the Andean fold-thrust belt becomes predominantly east vergent.

3.2.3. Balance. A pin line within the Lago Poopo basin was used to determine the shortening within the Paleozoic rocks of the backthrust belt. The backthrust belt was line length balanced from the pin to the last west verging thrust in Ordovician rocks. The Corque syncline was balanced from the pin line westward to the western edge of the cross section. Shortening estimates are

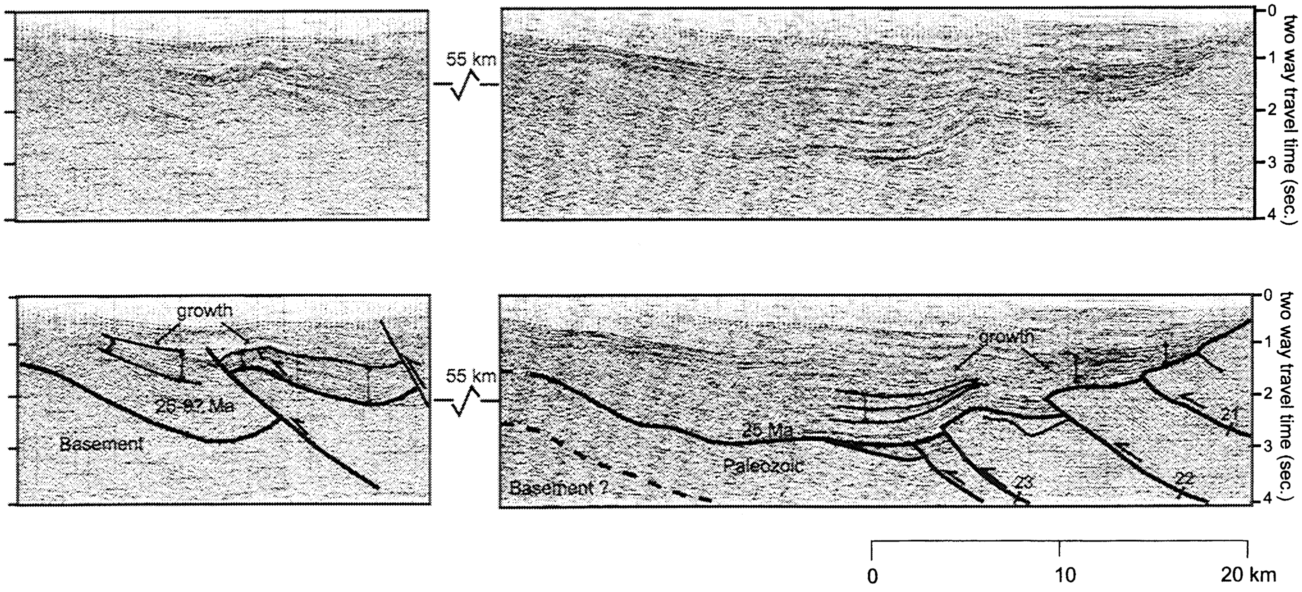

Figure 12. Seismic data and interpretation showing deformation and growth of Tertiary sediments to the east and west of the Corque syncline (not shown). Location of seismic line is roughly along same line of section as Figure 11.

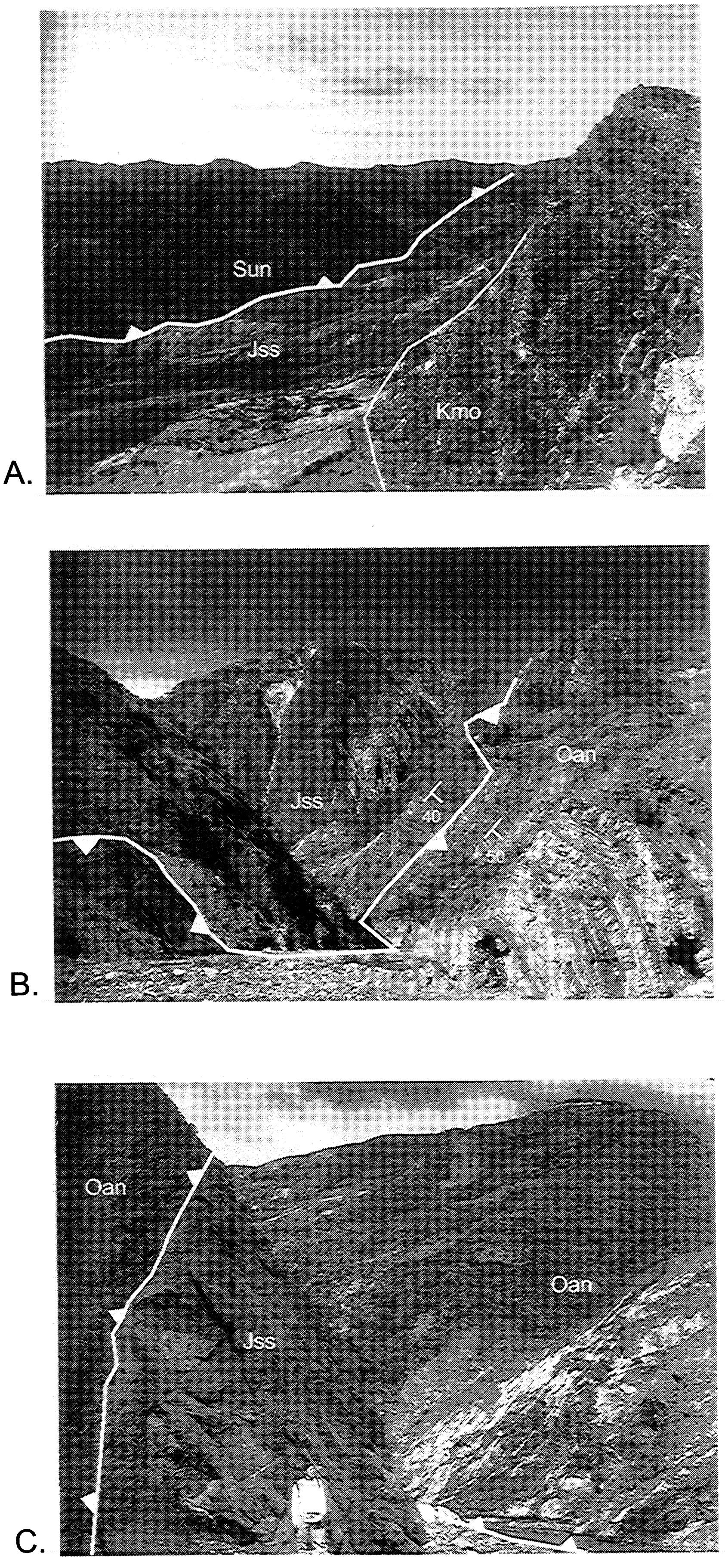

Figure 13.

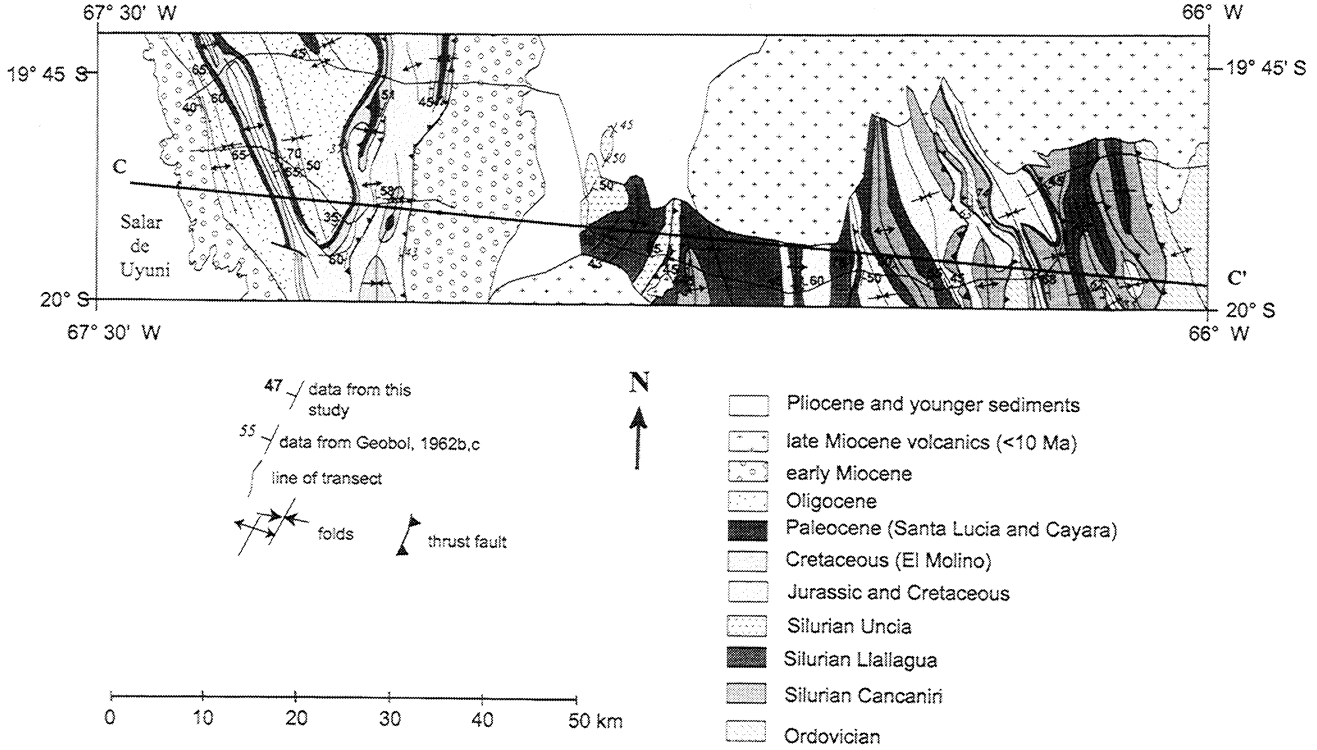

Figure 14. Generalized geologic map of the Rio Mulato and Kilipani fold-thrust belt (simplified from *GEOBOL*, [1962a, 1962b, 1962c] and our own mapping).

listed in Table 1. These estimates are also a minimum because of unaccounted-for strain.

3.3. Southern Cross Section (Rio Mulato-Kilpani Sector)

3.3.1. Stratigraphy. The southern sector of the backthrust belt also consists of rocks ranging in age from Ordovician to upper Tertiary synorogenic sediments. Compared to the northern and central sectors, there has been much greater pre-Jurassic erosion and much less Andean-age erosion. As a result, late Mesozoic rocks are exposed over large areas of the backthrust belt at this latitude and rest directly on lower Silurian rocks (Figure 3).

The main detachment horizon in the southern sector is within Ordovician rocks. The predominant Ordovician lithologies change to the south and to the west. In the northeastern Bolivian Andes the Ordovician can be divided into the three distinct lithologies described previously. However, south of 20°S and west of 66°W the thick quartzite beds that characterize the San Benito Formation and the siltite to quartzite beds that defined the Anzaldo Formation become much thinner and less prevalent. The dominant lithology of the Ordovician in southern Bolivia (~21°S) is shale/phyllite with minor sandstone beds [*Kley*, 1996; *Kley et al.*, 1997]; the total thickness is up to 9 km. These predominantly fine-grained siliciclastic marine sedimentary rocks were deformed and metamorphosed during a Paleozoic orogeny [*Baby et al.*, 1992; *Sempere*, 1995; *Kley et al.*, 1997]. This Paleozoic deformational event is not known north of 20°S latitude in Bolivia [*Sempere*, 1995]. Similar to the stratigraphy of the central sector, the Ordovician strata in the southern sector are conformably overlain by the Cancañiri and Llallagua Formations [*Sempere*, 1995; *Sempere et al.*, 1991]. Here the Cancañiri and Llallagua Formations reach their greatest thicknesses, 1500 m and >1500 m, respectively [*Gagnier et al.*, 1996; *Suarez-Soruco*,

Figure 13. Photographs showing relationship of Ordovician roof sheet to Jurassic footwall rocks. (a) Photograph showing hanging wall/footwall relationships on the east side of the Ordovician roof thrust. Photograph is taken looking south along the footwall cutoff in Jurassic (Jss) through Cretaceous (Kmo) rocks. These rocks are dipping 30°-40° to the west. The hanging wall is a horse in the Silurian Uncia Formation (Sun) identified as fault 6 on the cross section (Figure 11). The Silurian rocks are dipping 45° to the east. Location of photograph is indicated by *5 on Figures 9 and 10 and *3 on Figure 11. (b) Photograph showing hangingwall/footwall relationships on west side of Ordovician roof thrust. Orientations of Jurassic and Ordovician beds are close to parallel, dip west, and indicate a flat on flat relationship. (c) Photograph taken where east and west dipping Ordovician faults join (Figures 9 and 10, *3), looking south. Orientations of beds are east Ordovician Anzaldo Formation (Oan), N34°W 70°NE, west Oan, N35°W 57°SW and Jss, N40°W 47°SW.

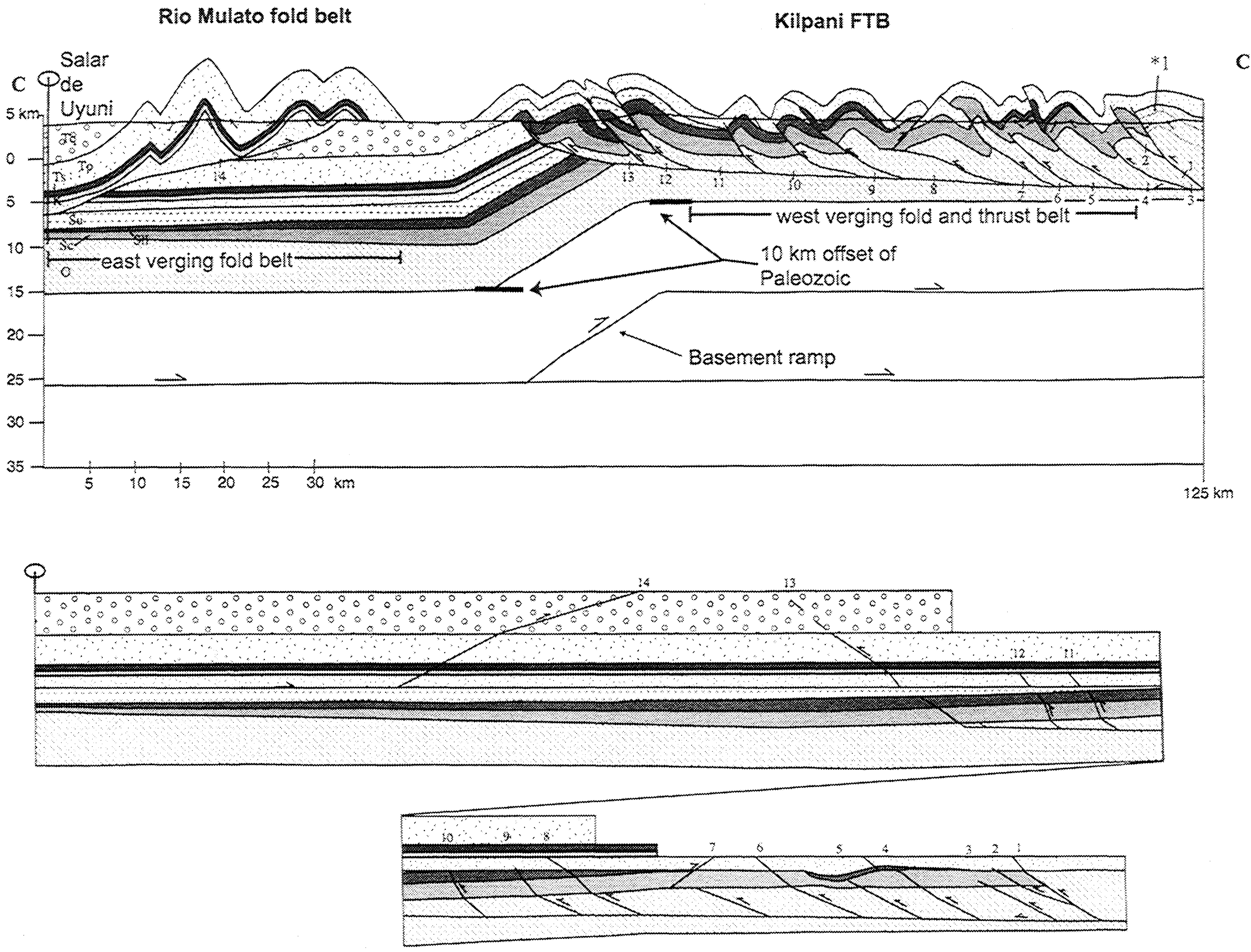

Figure 15. Balanced cross section and restored section for the Rio Mulato and Kilipani fold-thrust belt. See Figures 2 and 14 for location and Figure 3 for key to stratigraphic formation names. Starred numbers identify points discussed in text, and numbered thrusts refer to sequence of thrusting. Upper line between C and C' represents the modern topographic surface.

1995]. At the eastern edge of the southern sector of the backthrust belt the Llallagua Formation grades transitionally into the Silurian Uncia Formation. Upper Mesozoic rocks rest unconformably on upper Ordovician and lower Silurian rocks in the southern sector. This unconformity is higher in the stratigraphy to the west than in the east, complicating pre-Andean and Andean structures. The restored section (Figure 10) illustrates this slight angular unconformity by showing horizontal Jurassic and Cretaceous rocks resting on progressively older Silurian and then Ordovician rocks toward the west.

The Jurassic through Paleocene rocks of the southern Altiplano and Eastern Cordillera are referred to as the Puca Group [*Sempere,* 1995]. The Puca Group is interpreted as the fill of an Andean back arc basin [*Sempere,* 1995]. In the area of the southern sector the lower rocks of the Puca Group are conformable with the older Paleozoic rocks and are generally preserved in synclines. The upper part of the Puca Group, consisting of the Aroifilla, Chaunaca, El Molino, and Santa Lucia Formations, is deformed in the east verging fold belt of the Rio Mulato area (western part of the southern sector) (Figures 14 and 15). We interpret the evaporite-bearing Aroifilla and Chaunaca Formations to be the detachment horizon for the large salt-cored Rio Mulato fold belt. The Cayara Formation rests on top of the Santa Lucia Formation and in turn is overlain by the Oligocene-Miocene Potoco Formation, which is 3-3.5 km thick in the Rio Mulato area [*Sempere et al.,* 1997; *Horton et al.,* 2001]. The Potoco is overlain by up to 5 km of sandstone, conglomerate and volcanic rocks of the Tambillo and Quehua Formations [*GEOBOL,* 1962d].

3.3.2. Structure. The major structural features of the southern sector of the backthrust belt include a salt-cored fold belt in the Rio Mulato area, a 10 km high basement step that separates the Rio Mulato fold belt in the west from the Kilpani thrust belt in the east, and a fault propagation fold belt in Cretaceous and lower Silurian rocks (Figure 15). Like the other sectors, the style of deformation is a series of fault propagation folds cored by thrusts from the basal detachment horizon. In the southern sector the folds are cored by thrusts in Ordovician rocks. The detachment horizon within the Ordovician rocks is less constrained than in the northern sector because the Ordovician rocks only surface on a few thrusts. However, the short wavelength of the folds (many of which are also in the late Mesozoic rocks) and the common regional elevation of many of the Jurassic-cored synclines suggest a relatively shallow and uniform detachment horizon. The Ordovician detachment is interpreted to dip ~3° westward with respect to the top of the Ordovician. With respect to the base of the Jurassic rocks the main detachment dips <0.5° to the west (Figure 15).

3.3.2.1. Basement offset: The ~10 km basement step between the predominantly Paleozoic rocks to the east and the Tertiary rocks to the west is also seen in the Rio Mulato-Kilpani thrust system. The basement-cover contact is buried 15 km under the Rio Mulato fold belt, but the bulk of the Paleozoic section is exposed at the surface only 20 km to the east (Figure 15).

3.3.2.2. East verging fold belt: The Rio Mulato fold belt is a series of large amplitude (up to 8 km) salt-cored folds in Cretaceous and younger rocks, which detach in gypsum of the Aroifilla and Chaunaca Formations. Many of the folds are broken by minor thrust faults that verge east (Figure 14). The gypsum breaches the surface at the anticlinal crests of the folds, creating gypsum diapirs. We interpret the gypsum to be "in situ" because of the conformable bedding of the gypsum and the Chaunaca Formation along the edges of the diapirs. The Rio Mulato fold belt is thrust over the Miocene synorogenic sediments of the Quehua Formation on an east verging thrust fault that is interpreted to be the basal detachment for the fold belt (Figure 15).

3.3.2.3. West verging fold-thrust belt: The Kilpani section of the southern sector is a west verging fault propagation fold belt, similar in style to the fault propagation folds in the northern sector. The thrust faults lose displacement upward, and the shortening is taken up by folding. The eastern boundary of the cross section is the first major thrust carrying Ordovician rocks in the hanging wall (Figure 15, *1). No evidence exists for roof sheets or duplexes in this cross section of the backthrust belt, indicating that significantly less shortening is expressed at the surface. The disparity in shortening between the northern and central cross sections and the southern cross section may suggest the presence of unrecognized subsurface structures, particularly between the Rio Mulato fold belt and the backthrust belt.

3.3.3. Balance. The southern cross section was line length balanced from the western edge of the cross section (near Salar de Uyuni) to the easternmost thrust in Ordovician rocks. All of the units were line length balanced except for the Cretaceous Aroifilla and Chaunaca Formations within the Rio Mulato fold belt. These Cretaceous units were area balanced and retrodeformed to a collective length of 47 km for a 1.2 km thick bed (Figure 15). Similar to the other sectors, many of the thrusts shown on the restored section (especially in the Silurian units) are steep (45°-60°), and are interpreted to be a result of fault propagation folding. Shortening estimates for the southern sector are listed in Table 1.

3.4. Comparisons Among the Three Cross Sections

3.4.1. Common entities. The northern, central, and southern cross sections display older units and deeper exposures in their eastern portions than in the west, the thrusts tend to verge and cut up section to the west, and the style of deformation is similar for hundreds of kilometers along strike. The duplexes in the eastern parts of the Huarina (northern) and Lago Poopo (central) sectors require that at least in those sections, the thrusts broke in sequence from east to west [*Boyer and Elliott,* 1982]. The combination of these features is strong support for a westward verging, westward younging backthrust system that extends along a significant portion of the central Andean fold-thrust belt.

The most noticeable feature in all three cross sections is the large, half-crustal scale offset in the basement. This large offset between rocks exposed on the Altiplano and those exposed within the Eastern Cordillera has been recognized on earlier regional cross sections. *Baby et al.* [1997] and *Rochat et al.* [1996, 1999] interpreted this step to be due to a normal fault. They proposed that a half-graben formed on the Altiplano to allow for rapid sedimentation during the middle Miocene (within the Corque syncline). However, seismic sections (Figure 12) [*Lamb and Hoke,* 1997] do not show the eastward fanning dips expected for rapid sedimentation on a down-to-the-west normal fault. The relationships visible on seismic are consistent with compressional growth structures over fault propagation folds under the Lago Poopo basin (Figure 12) and a westward diverging angular unconformity in middle to late Miocene rocks in the east limb of the Corque syncline [*Lamb and Hoke,* 1997]. The latter relationship indicates westward rotation of the eastern limb of the syncline. Moreover, structural inversion of a half-graben will not produce the well-documented geometry of the Corque syncline. A lack of any extensional structures between the fold-thrust belt and the syncline also supports a non extensional environment for the Corque syncline.

In the schematic cross sections of *Lamb and Hoke* [1997] the contact between the Paleozoic rocks and the overlying Tertiary sediments is depicted as irregular and varies in depth across strike. In the vicinity of the Corque syncline a step in this contact allows for the excessive sedimentation recorded in this area. However, no structural interpretation was suggested by *Lamb and Hoke* [1997] for how or why this ~10 km thick depocenter would be focused along the axis of the Corque syncline.

Another mechanism that could explain the large basement offset between the backthrust belt and the Tertiary sediments is a west verging basement thrust. Although this mechanism may explain the basement offset, it also creates significant problems. The first is the large discrepancy in the amount of shortening recorded in the cover rocks of the backthrust belt and the amount that could be accommodated by a west verging basement thrust. If the amount of shortening on the hypothetical basement thrust were large, slip would need to be fed into the Altiplano, where there are no structures that could accommodate such a high percentage of shortening. If the amount of shortening on this west verging basement thrust were small, a large discrepancy would be created between the amount of shortening in the basement versus that accommodated by the backthrust belt.

The along-strike continuity of the offset in the Paleozoic rocks strengthens the argument that this step is a dominant feature within the hinterland of the central Andean fold-thrust belt. We propose that this laterally continuous step in the basement was produced as a large east vergent basement thrust moved up and over a ~12 km basement ramp. The interpretation of this step as a large ramp within the basement is supported by Paleozoic hanging wall and Tertiary footwall cutoff relationships documented in the northern sector (Figures 4 and 6) as well as seismic interpretations in the Poopo basin and the uniform thickness and geometry of the beds within the Corque syncline. The interpretation of this step as a ramp implies that the overlying

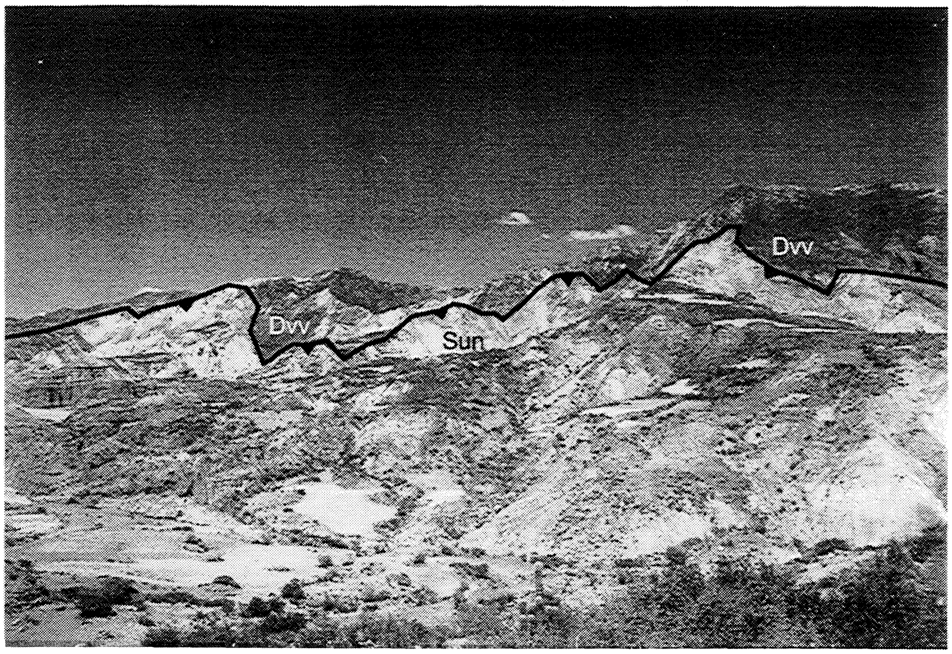

Figure 16. Photograph of high angle fault (45°-65°) with low (subparallel) fault to bedding angle. Fault, Silurian Uncia Formation (Sun) and) Devonian Vila Vila Formation (Dvv) all dip steeply (45°-65°) to the east. Location of photograph is along strike of *2 (Figures 4 and 5) to the southeast.

Paleozoic through Tertiary rocks were passively folded into a monocline as the basement thrust cut up section eastward and was emplaced beneath what is now the Eastern Cordillera. The eastward displacement of the basement thrust was partially accommodated by the westward propagation of the backthrust belt in the cover section. The backthrust belt thus forms the roof system of a crustal scale passive-roof duplex [*Banks and Warburton*, 1986]. This interpretation is also consistent with an overall compressional environment for the formation of the Andean plateau, and an eastward evolving Andean fold-thrust belt.

Although the steepness of many faults within the Eastern Cordillera and their apparent minimal offsets have been used as arguments for the low shortening potential of this part of the fold-thrust belt [e.g. *Martinez,* 1980], *Sheffels* [1990] suggested that the repeated juxtaposition of steep stratigraphic units across these faults requires that the dips of the faults flatten with depth, thus dramatically increasing the shortening accommodated by an individual fault. Our work suggests that two sets of steep faults are present within the backthrust system. The first set consists of faults that typically dip 45°-65° but are subparallel to bedding, indicating that they formed as detachments at much lower angles (subhorizontal) (Figure 16). These faults are located within the interior parts of the backthrust belt in the northern and central sectors. These initially subhorizontal faults were then rotated into their present steep dips by displacements on younger, westward faults. The second set of faults cut steeply up dip as seen in the field, on maps, and in the restored section (Figure 17). The steep dips of most of these faults are the result of the development of fault propagation folds. The shortening in these rocks was accomplished first by folding above a propagating fault tip and later by faulting [*Mitra*, 1990; *McNaught and Mitra*, 1993].

3.4.2. Lateral structural variations. The three cross sections exhibit significant changes in shortening amounts from north to south, particularly within the backthrust belt. The sector with the longest undeformed length is the central sector (308 km). Here the backthrust belt has shortened 142 km or 46%. The original length of the northern cross section was 232 km, and the amount of shortening is 132 km, but the percent shortening is larger (57%) than to the north. The most significant difference is seen by comparing these shortening estimates to the shortening estimates in the southern sector. In the southern sector the original length of the backthrust belt was 130 km, and it has shortened 43 km or 33%. The possible explanations for the discrepancy include unrecognized shortening in the backthrust belt, either unmapped duplex structures east of the cross section (near the Potosi area; Figure 2) or buried west vergent structures east of the Rio Mulato area, or a real gradient in width of and shortening accommodated by the backthrust belt that decreases to the south. The along-strike projection of the duplexes, both in the northern sector and the central sector, lies east of the Kilpani cross section. In this region, maps show angular unconformities between the Ordovician rocks and the overlying Jurassic and Cretaceous rocks [*GEOBOL*, 1996b], making recognition of Andean-age deformation difficult. Also, the map patterns of the structures in this area give little indication of duplexes [*GEOBOL*, 1996b]. The shortening difference may be a reflection of buried thrusts west of the backthrust belt and east of the Rio Mulato fold belt. In this area there is a depositional basin similar to the Poopo basin (Figures 9 and 11). Reflection seismic data indicate buried folds and faults within the Poopo basin (Figure 12)[*Lamb and Hoke*, 1997]. There is also evidence of buried folds and faults south of the southern sector, west of the

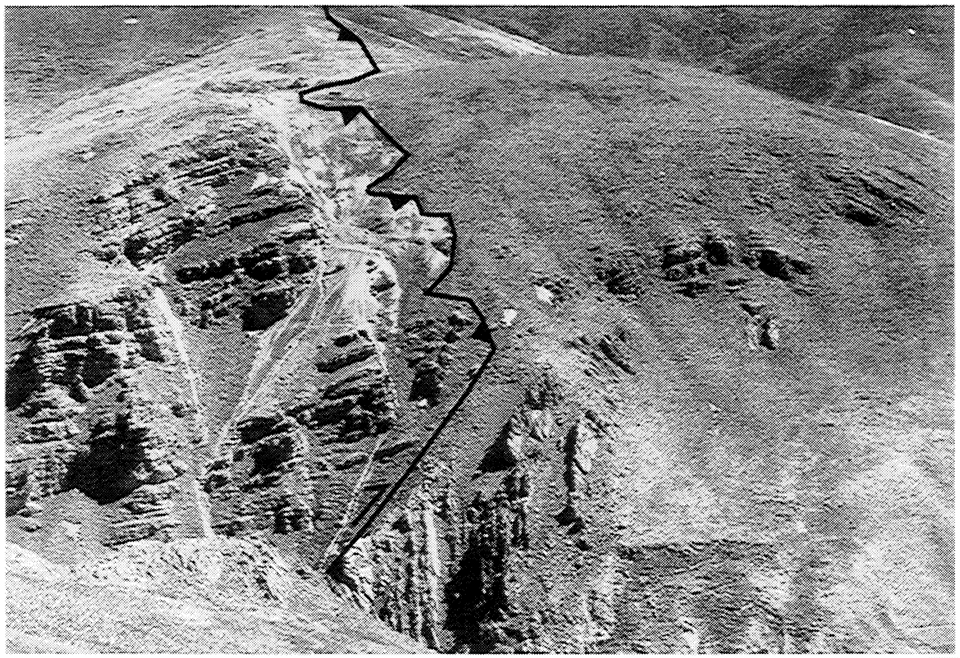

Figure 17. Fault in Devonian rocks showing high fault to bedding angle. The fault is located in the western portion of the backthrust belt (northern sector).

major west verging San Vicente fault [*Baby et al.*, 1990]. In the southern cross section the basement step and the western edge of the backthrust belt were conservatively chosen as the westernmost extent of the exposed Paleozoic rocks. This leaves 20 km of covered geology that may include the westward extension of the backthrust belt, similar to the covered fold-thrust belt to the north and south. The third possibility is that the amount of shortening accommodated by the backthrust belt decreases to the south. The total amounts of shortening vary from 141 to 189 km in the north to 85 km in the south, documenting that the decrease in shortening amounts is real. The decrease in shortening accommodated by the backthrust belt may reflect a decrease in shortening within the entire fold thrust belt to the south, or an increase in the amount of shortening taken up by east verging structures.

3.5. Composite Cross Sections

The composite cross sections shown in Figure 18 link the west verging backthrust belt to the main east verging Andean fold-thrust belt. The hinterland cross sections presented in this paper are joined with the previously published cross sections from the Eastern Cordillera to the sub-Andean zone [*Rochat et al.*, 1999; *Baby et al.*, 1997; *Schmitz and Kley*, 1997; *Kley*, 1996; *Kley et al.*, 1996]. No attempt is made to depict kinematic detail at the scale of the composite cross sections because the level of detail in our cross sections is not matched by previous cross sections and because of significant across-strike offset between section lines. However, the basement thrust we propose as a mechanism to lift the Eastern Cordillera relative to the Altiplano coincides with the basement thrusts that elevate the Eastern Cordillera with respect to the sub-Andean zone in the east [*Kley*, 1996; *Kley et al.*, 1996; *Schmitz and Kley*, 1997; *Baby et al.*, 1997; *Rochat et al.*,1999]. Viewed in this context, the west and east verging sections of the Eastern Cordillera are structurally elevated areas of "thin-skinned" deformation underlain by basement megathrusts. *Kley* [1999] described a similar two-stage geometry of basement and cover deformation to explain both the elevation and tight deformation seen in the Inter-Andean zone (the area between the Eastern Cordillera and the sub-Andean zone) of the fold-thrust belt. The composite cross sections (Figure 18) show 100-200 km of eastward transport on basement thrusts that carry 12-15 km thick basement thrust sheets. The size (thickness and length) and the transport distance are similar to other megathrusts in the internal portions of fold-thrust belts [*Hatcher and Hooper*, 1992].

The crustal duplex in the hinterland of the northern section (Figure 18a) is constrained only by the need to fill space beneath surface exposures of basement rocks in the western Altiplano [*GEOBOL*, 1995d]. The structural relief on the basement cover contact in this region must be ~12 km. The growth of this basement high is seen in growth structures imaged on seismic lines west of the Corque syncline (Figure 12). These growth structures diverge eastward, suggesting that the basement was uplifted with respect to the syncline from 25 to 5 Ma. The pronounced 9 Ma angular unconformity on the east limb of the Corque syncline and the conformable sequence on the west limb suggest that major growth of the duplex was post 9 Ma [*Lamb and Hoke*, 1997]. The western duplex formed by out-of-sequence hinterland shortening. Compression, which built this duplex, also folded the western limb and faulted both the western and eastern limb of the syncline. Slip associated with the growth of this duplex was fed eastward into the sub-Andean zone along the lower basement thrust. It is likely that the southern cross

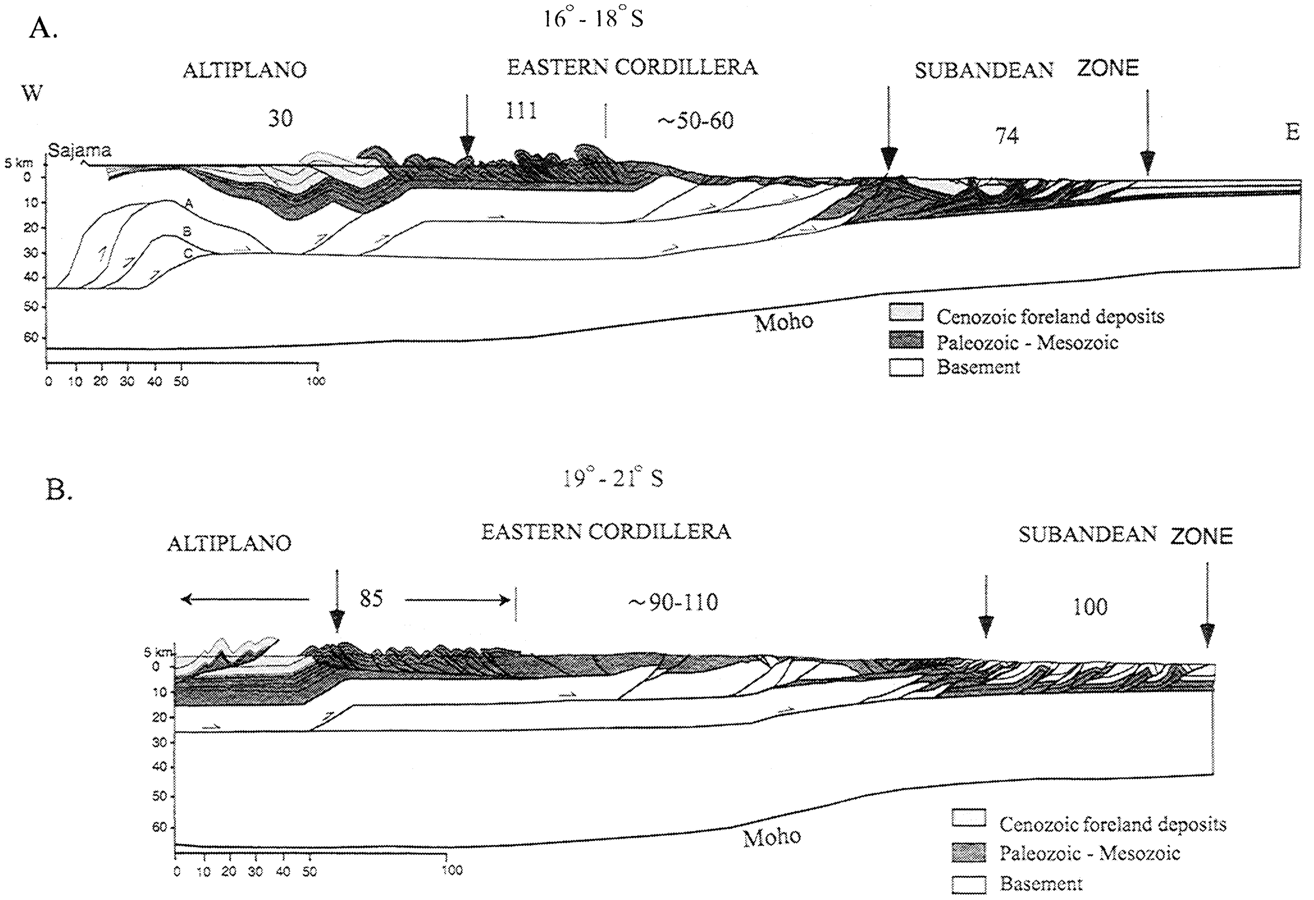

Figure 18. Composite cross section across the Andean fold-thrust belt. (a) The Corque syncline and Huarina fold-thrust belt combined with the regional cross section of *Baby et al.* [1997] and *Rochat et al.* [1999]. (b). The Rio Mulato and Kilpani fold-thrust belt combined with the cross section of *Kley* [1996], *Kley et al.* [1996] and *Schmitz and Kley* [1997]. Vertical lines represent the eastern boundary of our cross sections; arrows indicate boundaries between physiographic provinces. Numbers are shortening estimates from the published cross sections and our own.

section has a similar geometry to the west. Seismic reflection data from the northeastern portion of the Salar de Uyuni show the gentle eastward dip and possible growth in the synorogenic sediments (proprietary data YPFB). These gentle eastward dips may reflect the same growth of the basement duplex as proposed for the westward growth seen on the seismic sections to the north.

The basement duplex and the main decollement for the thrust belt are both very deep (35-40 km) with respect to a brittle-ductile transition zone in an orogenic system [*Carter and Tsenn*, 1982; *Wernicke*, 1990; *Beck et al.*, 1996]. Although these faults are depicted as discrete surfaces in the cross sections, the deformation was most likely in the ductile regime and the lower detachment may be a diffuse crustal shear zone.

3.6. New Estimates of Shortening

The shortening estimates produced on the basis of balanced cross sections across the backthrust belt and Altiplano significantly increase shortening estimates for the entire Andean fold-thrust belt (Table 2). Documented shortening estimates for the Andean fold-thrust belt range from 191 to 260 km [*Kley and Monaldi*, 1998]. By combining new shortening estimates for the backthrust belt and Altiplano with those previously published for the east vergent portion of the fold-thrust belt, we increase minimum shortening estimates for the entire Andean fold and thrust belt by 63-145 km in the north and 25-35 km in the south (Table 2). Combining new shortening estimates from the hinterland with previously published estimates is difficult because, typically, shortening estimates for the fold-thrust belt mention shortening in the Eastern Cordillera as a whole and do not differentiate the amount of shortening accommodated by the west vergent system or the east vergent system. For the northern section, *Baby et al.* [1997] and *Rochat et al.* [1999] estimate 117 km of shortening accommodated from the Eastern Cordillera to the Altiplano at the latitudes of 15°–18°S. We propose that ~50-60 km of this shortening is within the east verging portion of the Eastern Cordillera. By combining our new estimate for the Altiplano and backthrust belt with the estimate of *Baby et al.* [1997] and *Roeder* [1988] for the east vergent portion of the fold-thrust belt, orogen-scale shortening estimates in this area increase to a

Figure 19

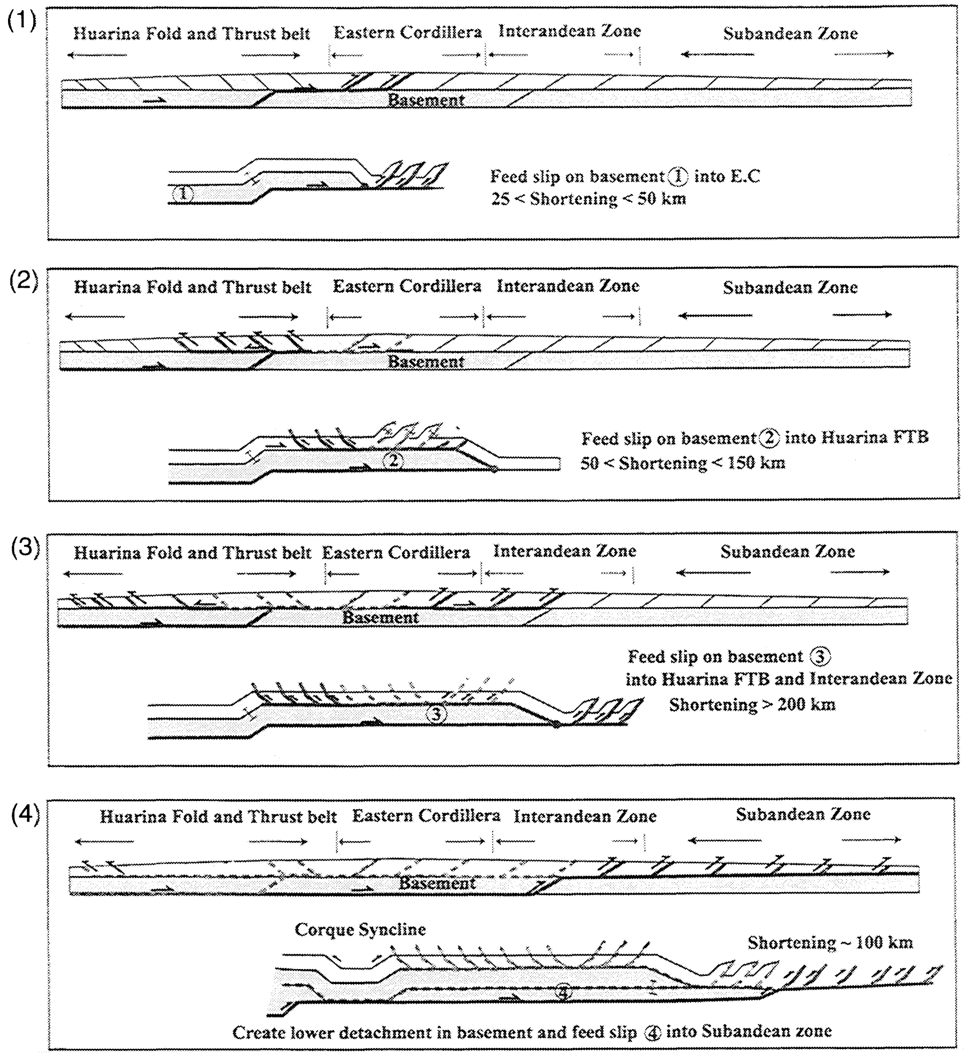

Figure 19. Kinematic development of the central Andean backthrust belt. In each panel the upper cross section represents the undeformed section (shaded basement and white cover) and displays the locations of the active thrust systems within the context of the undeformed stratigraphy. Solid dark lines are active faults and dashed shaded lines are inactive faults. Numbers 1-4 are the time steps discussed in the text and show the sequential development of the backthrust belt with the active thrusts in bold (dark) and the inactive thrusts shown by dashed (shaded) lines.

minimum of 265-336 km (Table 2). For the central section we combined and compared our shortening estimates with those of *Sheffels* [1988, 1990] concluding that shortening in the central portion of the fold-thrust belt was at least 330-337 km (Table 2). In the south, *Baby et al.* [1997] and *Kley et al.* [1997] suggested that there is 145-160 km of shortening in the Eastern Cordillera and in the Altiplano at the latitudes of 21°–22°S, with 20 km of this shortening within the Altiplano [*Baby et al.*, 1997] and 50 km within the west verging backthrust belt [*Kley et al.*, 1997] that extends 60 km farther east than the Kilpani sector. At the latitude of 20°S we propose that there is 85 km of shortening in the backthrust belt and Altiplano, increasing the orogen-scale shortening estimates to 249-295 km. In general, the new estimates are 74-145 km greater than estimates previously proposed in the north, 63-138 km greater in the central sector, and up to 25-35 km greater than previous estimates to the south (Table 2). The uncertainty in the minimum shortening estimates reflects the range of documented shortening proposed for the Eastern Cordillera and sub-Andean zone in the literature [*Kley and Monaldi*, 1998]. On the basis of the kinematic history proposed in section 4 we suggest that the greater shortening estimates (300-340 km) more accurately reflect the shortening in the Andean fold-thrust belt. Although determined by completely independent means, the shortening in the central Andean fold-thrust belt that we propose on the basis of this study matches shortening estimates based on oroclinal rotation and isostatically balanced area calculations [*Isacks*, 1988; *Lyon-Caen et al.* 1985].

The increase in shortening estimates in this study compared to previous studies may reflect a combination of several different factors. The first is the recognition of structures in the western

Table 2. Composite Shortening for the Andean Fold-Thrust Belt[a]

Location	Hinterland	Eastern Fold-Thrust Belt	Foreland	Total
Northern sector				
Shortening estimate in Figure 18.	141 km(*)	~50-60 km(2)	135 km(9)	336-265 km
Other published estimates	117 km(2)		74 km(2)	191 km(2,7)
Central sector				
Our shortening estimate	189 km(*)	54 km(11)	60 km(1) 67 km(11)	303-310 km
Other published estimates	30 km(8)	210 km(10)		240 km(7)
Southern sector				
Shortening estimate in Figure 18.	85 km(*)	~90-110 km(5,6)	100 km(4)	275-295 km
Other published estimates	20 km(2) + 50 km(6)	80-90 km(5) 145 km(2)	74 km(3) 86 km(2)	224-260 km 231 km(2)

[a] Hinterland heading includes both the Altiplano and backthrust belt except where noted in the references. Eastern fold-thrust belt heading includes all east verging structures from the backthrust belt to the Subandean zone, and foreland heading refers to the deformation within the Subandean zone. Ranges for total shortening are highest and lowest estimates based on the range in shortening values for the Subandean zone given by different authors. References (in parentheses) are as follows: *, this study; 1, Baby et al., 1993; 2, Baby et al., 1997; 3, Dunn et at., 1995 4, Herail et al., 1990; 5, Kley, 1996; 6, Kley et al., 1997; 7, Kley and Monaldi, 1998; 8, Lamb and Hoke, 1997 (only includes Altiplano); 9, Roeder, 1988; 10, Sheffels, 1990 (entire fold-thrust belt excluding Altiplano); 11, Sheffels; 1988.

part of the Eastern Cordillera as predominantly Andean. Many of the 1:250,000 and 1:100,000 scale maps that were field checked for this study show unconformable relationships between the Paleozoic rocks and the overlying Jurassic through Cretaceous section (e.g., *GEOBOL*, 1994; 1995c). The field mapping accompanying this study indicated no significant angular unconformity between the Jurassic rocks and the underlying Paleozoic. In fact, at every location where the field transects encountered Jurassic and younger rocks in depositional contact, the bedding attitudes were completely conformable. Secondly, the detail in which the structures were mapped both in this study and on the existing GEOBOL maps led to the recognition of duplexes and roof sheets, which significantly increased the shortening estimates for the northern and central cross sections. The third factor is the importance of taking cross sections to a basal detachment for accurately estimating shortening and interpreting surface geometries. A fundamental requirement of balanced cross sections is the recognition and interpretation of both hanging wall and footwall cutoffs because footwall ramps affect the structural level and the geometry of the overlying rocks and structures (*Boyer and Elliott*, 1982; *Woodward et al.*, 1985). Thus, taking the cross sections to a regional detachment level (basement) provided a means to recognize significant structures undocumented in previous studies and to provide support for interpretations of important regional structures such as the large basement steps [e.g., *Kley,* 1996].

4. Kinematic History

The development of the central Andean backthrust belt within the context of the regional kinematic history of the Andean orogenic wedge can be inferred from (1) the migration history of the Andean foreland basin system, (2) geometric constraints implied by the cross sections, (3) growth structures in syntectonic Tertiary sediments, and (4) ages of overlapping syntectonic sediments.

4.1. Paleocene Thrust Belt

The age of the onset of mountain building is most readily identified by the age of the oldest sediments associated with the growing orogenic wedge. Evidence for eastward propagation of the Andean orogeny can be extracted from the sedimentary record of its associated foreland basin system, which documents an eastward migrating fold-thrust belt from the Paleocene to present [*Sempere et al.*, 1997; *Horton and DeCelles*, 1997; *DeCelles and Horton,* 1999]. The presence of Paleocene foreland basin sediments in the Altiplano and Eastern Cordillera implies that a coeval, narrow, eastward propagating fold-thrust belt existed in Chile and westernmost Bolivia [*Sempere,* 1995; *Sempere et al.,* 1997; *Horton and DeCelles*, 1997; *Horton et al.,* 2001]. Structural evidence for the Paleocene fold-thrust belt may be covered by the Neogene volcanics of the Western Cordillera or may be found in the Paleocene-Eocene shortening in the Precordillera region of Chile [*Hammerschmidt et al.,* 1992; *Horton et al.,* 2001].

4.2. Transfer of Slip to Eastern Cordillera

The basement megathrust depicted in the cross sections is the connecting link between the proposed Paleocene fold-thrust belt and the structures in the Eastern Cordillera. We suggest that the fold-thrust belt propagated eastward along the basement thrust at or near the brittle-ductile transition zone, into the Eastern Cordillera. As the basement megathrust propagated up and over the basement ramp, it raised the Paleozoic rocks ~12 km above their regional structural elevation. The timing of this major tectonic event is weakly constrained. Sparse thermochronologic data from apatite and zircon fission track and ^{40}Ar/^{39}Ar cooling ages suggest exhumation in the Eastern Cordillera at ~40±5 Ma

[*Benjamin et al.*, 1987; *McBride et al.*, 1987; *Sempere et al.*, 1990; *Masek et al.*, 1994]. This late Eocene-early Oligocene cooling event may represent the uplift of the Eastern Cordillera as the megathrust sheet moved up and over the basement ramp (time step 1, Figure 19).

The detailed kinematic evolution of the backthrust belt with respect to the eastward propagating basement thrust sheet is schematically illustrated in Figure 19. Time step 1 shows a basement thrust fault, detaching along the brittle-ductile transition zone that ramped into the Eastern Cordillera and fed 25-50 km of slip into an emerging east verging fold-thrust belt. This created a structural flat on which the backthrust belt could propagate westward. At time step 2, thrusts in the Eastern Cordillera were locked; 50-100 km of additional slip on the basement thrust were accommodated in the cover rocks by development of west verging thrusts in the backthrust belt. Time step 3 is a final increment of 50+ km of slip on the basement thrust that was accommodated by further shortening in the backthrust belt and perhaps by forward breaking thrusts in the Inter-Andean zone. Thus, of the total 190+ km of shortening in the basement, 50+ km must have been taken up by eastward-breaking thrusts in the Eastern Cordillera, and the remainder produced the backthrust belt. Time step 4 shows a lower basement decollement (again along the brittle-ductile transition zone) that fed slip (100+ km) into the sub-Andean zone and perhaps created the hinterland crustal duplex that folded the Corque syncline. The minimum shortening required by this kinematic scenerio is 290+ km.

4.3. Development of the Altiplano Piggyback Basin

The emplacement of the basement megathrust sheet and associated shortening of the cover section must have thickened the crust of the Eastern Cordillera by at least 15 km. Flexural isostatic adjustment to this load would have depressed the footwall, flattened the half-crustal scale ramp, and produced topographic relief of ~1.5-2 km along the eastern edge of the Altiplano. The resulting topographic dam began to trap significant amounts of syntectonic sediment beginning at ~40 Ma, facilitating the development of the Altiplano piggyback basin. Initially, this sediment was derived mainly from the west, but by the time ~4 km of sediment had accumulated, an eastern provenance signature began to be recorded in the basin fill [*Hampton and Horton*, 2000]. As displacement on the basement megathrust continued, the thickness of sediment in the Altiplano basin increased, and the basin fill itself began to exert a significant load on the underlying lithosphere. Flexural compensation of the progressively increasing load would have gradually resteepened the angle of the basement megathrust ramp. Ultimately, the Altiplano basin accommodated 12-15 km of sediment, roughly equivalent to the height of the megathrust ramp. Growth structures in early to mid-Miocene sandstones and conglomerates (Coniri Formation) east of the Corque syncline record the approaching west verging backthrust belt (time steps 2 and 3, Figure 19). These growth structures include rotated unconformities [*Sempere et al.*, 1990], an angular unconformity up to 30° between the Coniri Formation and the underlying rocks [*Sempere et al.*, 1990; *Lamb and Hoke*, 1997], and growth folds and faults in Miocene strata overlying fault propagation folds in Paleozoic rocks near the western limit of the backthrust belt (Figure 12) [*Lamb and Hoke*, 1997]. It is plausible that older syntectonic sediments that were deposited in the Altiplano basin were eroded as they were transported eastward and incorporated into the backthrust belt.

4.4. Termination of the Backthrust Belt

Fold-thrust structures in the northern sector of the backthrust belt are overlapped by generally undeformed or slightly deformed sediments of the Salla beds [*Sempere et al.*, 1990] providing a constraint on the youngest possible activity in the backthrust belt. The fossiliferous Salla beds are well dated between 24 and 21 Ma [*McFadden et al.*, 1985; *Sempere et al.*, 1990; *Marshal and Sempere*, 1991]. From this time onward, deformation was fed into the easternmost Eastern Cordillera and, by late Miocene time [*Gubbels et al.*, 1993], into the sub-Andean zone (time step 4, Figure 19).

4.5. Hinterland Basement Duplexing

Growth structures in Tertiary sediments east of the Corque syncline and conformable sediments in the western limb [*Lamb and Hoke*, 1997] suggest that the basement duplex formed out of sequence with respect to the rest of the fold-thrust belt. The development of the crustal duplex in the west (thrusts A, B, and C, Figures 6, 11, and 18), which folds the western limb of the Corque syncline, occurred after displacement in the Huarina fold-thrust belt ceased. Growth structures imaged on seismic lines west of the Corque syncline suggest that the basement was uplifted with respect to the syncline from 25-5 Ma. The pronounced 9 Ma angular unconformity on the east limb of the Corque syncline and the more conformable sequence on the west limb [*Lamb and Hoke*, 1997] suggest the major growth of the duplex was post-9 Ma. Compression associated with the growth of this duplex folded the western limb and faulted both the western and eastern limbs of the syncline. On the basis of the 9-5 Ma timing of deformation within the Corque syncline [*Lamb and Hoke*, 1997], apatite fission-track ages marking increased uplift and denudation in the Eastern Cordillera from 15-7 Ma [*Benjamin et al.*, 1987; *Masek et al.*, 1994], the ~ 10 Ma age of the San Juan del Oro erosional surface which truncates compressional structures in the Eastern Cordillera [*Gubbels et al.*, 1993; *Kennan et al.*, 1997], and the post-10 Ma initiation of thrusting in the sub-Andean zone [*Gubbels et al.*, 1993], we propose the following sequence for late Miocene deformation. Pre-10 Ma, motion on the basement megathrust ceased as the Andean fold-thrust belt initiated a lower basement decollement, again on the brittle-ductile transition zone, 20-30 km below the surface, which began to feed slip from the hinterland of the orogen into the sub-Andean zone (Figures 11, and 12, time step 4). Basement duplexing in the hinterland of the plateau initiated at the same time, perhaps as a taper-building mechanism [e.g., *Mitra,* 1997], and served as the driving force behind the folding of the Corque syncline. During this time frame, shortening within the sub-Andean zone was most likely balanced by distributed shortening of the lower crust in the eastern Cordillera and Altiplano as proposed by *Isacks* [1988], *Gubbels et al.* [1993], and *Lamb and Hoke* [1997] to account for the remaining 1.5-2.0 km of uplift post-10 Ma [*Gubbels et al.*, 1993, *Gregory-Wodzicki et al.*, 1998].

5. Basement Thrusts and Ramps

The proposed basement megathrust sheet is remarkable for its length, thickness, and lack of internal deformation. Such

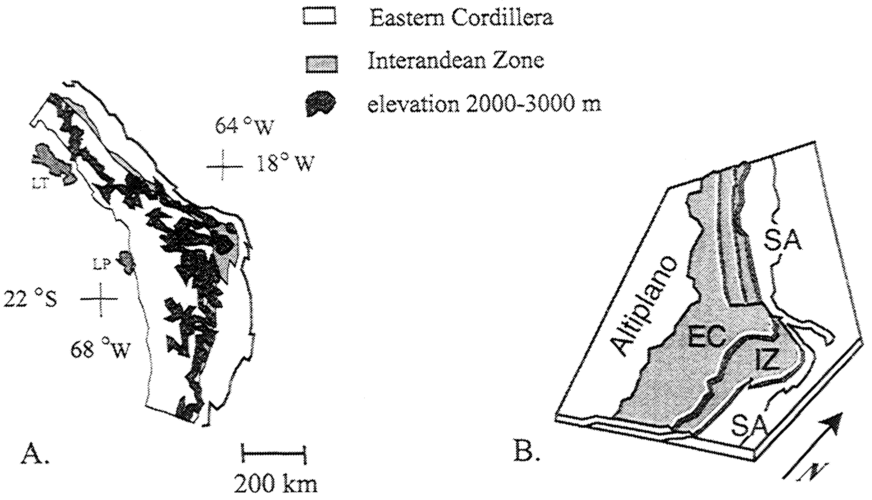

Figure 20. Correlation between the structural elevations of the basement megathrusts and major steps in topography. (a) In the south there is a strong correlation between the Inter-Andean zone and topographic elevations of 2000-3000 m. In the north the break in elevation occurs in the Eastern Cordillera (*Kley*, 1999). LT, Lake Titicaca; LP, Lago Poopo. (b) Structural elevations due to the overlap of basement megathrusts (Paleozoic cover not shown). There are two significant basement ramps. The first is on the eastern edge of the Altiplano and the second is under the Eastern Cordillera/Inter-Andean zone transition. From *Kley* [1999] (Reprinted by permission of Excerpta Medica Inc.).

megathrusts are common in the medial to hinterland parts of major orogenic wedges. Examples of megathrusts in other orogens include the Blue Ridge-Piedmont sheet (southern and central Appalachians; *Mitra* [1978]; *Hatcher and Hooper* [1992]; *Boyer and Elliott* [1982]), Canyon Range and Willard thrust sheets (Cordilleran fold-thrust belt; *Yonkee* [1992]; *DeCelles et al.* [1995]), and the Main Central thrust (Himalaya; *Schelling*, [1992]). Basement megathrusts carry large cohesive sheets that are typically 3-10 km thick and facilitate horizontal displacements of up to 350-450 km [*Hatcher*, 1989; *Hatcher et al.*, 1989]. The main decollement surface for the crystalline megathrusts is the thermally weakened brittle-ductile transition zone [*Hatcher and Hooper*, 1992]. Thus the rocks contained in the megathrust sheets are very strong (crystalline basement or thick uniform sheets of quartzite) with respect to their decollement than thrust sheets that occupy the frontal portions of the thrust belt. The initial detachment at the back of an orogenic wedge typically takes place at the brittle-ductile transition zone (15-20 km), which may be well within basement rocks, depending on the thickness of the overlying sediments [*Bruhn et al.*, 1986; *DeCelles and Mitra*, 1995; *Mitra*, 1997]. Owing to the ductile nature of this decollement, the basal detachment angle (near zero) remains constant over a large area creating a uniform slab geometry [*Hatcher and Hooper*, 1992]. The geometry and distance of travel of the thick-skinned sheets affect the level that they perturb the geothermal gradient in their footwalls. If the perturbation is significant enough, it may extend thick-skinned thrusting farther toward the foreland [*Mitra*, 1997]. The generation and emplacement of such megathrust sheets are responsible for much of the crustal thickening within a fold-thrust belt [*Hatcher and Hooper*, 1992]. Duplexes and ramps form in crustal rocks where the faults at the base of the megathrust sheets can no longer propagate along the brittle-ductile transition zone. At this point it becomes mechanically easier to ramp into the upper crust or if possible into the platform sequence. These crustal ramps and/or duplexes may be a mechanism for uplift or formation of high plateaus [*Hatcher and Hooper*, 1992]. *Kley* [1999] showed a strong correlation between the location of the basement megathrust sheets and significant steps within the topography of the Andean plateau and fold-thrust belt. This is most readily seen in the comparison of structural elevations to the overlap patterns of the large basement sheets (Figure 20).

6. Conclusions

The following points summarize our conclusions.

1. The central Andean backthrust belt consists of an ~600 km long, ~100 km wide belt of predominantly west verging folds and thrust faults that developed along the western flank of the Eastern Cordillera. These thrusts step up section from Ordovician to Devonian rocks toward the west.
2. Available timing constraints suggest that the backthrust belt was active from late Eocene to early Miocene time.
3. The backthrust belt facilitated the eastward emplacement of an ~100 km long basement megathrust sheet in the medial part of the Andean orogenic wedge. The front of the orogenic belt jumped ~200 km eastward, into the present Eastern Cordillera, during the emplacement of the megathrust sheet.
4. The strong correlation between the eastern edge of the basement megathrust and the eastern edge of the Andean plateau suggests that megathrusts, or the stacking of coherent sheets of basement, may play an important role in the formation of the plateau.
5. The Corque syncline developed in two stages: Its eastern limb may have initially formed above the main ramp in the basement megathrust, and its western limb formed later, proba-

bly during the late Miocene-Pliocene time, in response to basement duplexing in the hinterland of the western Altiplano. Compression and out-of-sequence basement faulting associated with the basement duplex is proposed to be the driving force that faulted both limbs.

6. The Altiplano basin developed during Oligocene-recent time as an immense piggyback basin, hemmed in along its eastern flank by a basement ramp and growing fold-thrust belt in the Eastern Cordillera and on its western flank by hinterland thrust-related topography and, since the late Oligocene time, by the magmatic arc.

7. The addition of minimum shortening estimates from the backthrust belt to existing estimates from the eastern part of the fold-thrust belt raises the total minimum shortening in the central Andes to as much as 340 km. Documentation of additional shortening in the western Andes must await further study. In any case, the total amount of shortening is likely to fall well within the amounts needed to explain present crustal thickness.

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