Tectonic inversion in the Santa Barbara System of the central Andean foreland thrust belt, northwestern Argentina

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[1] The Santa Barbara System (SBS) of northern Argentina is a 400 km long segment of the Subandean foreland thrust belt. It is characterized by predominantly west verging, relatively high-angle thrust faults. Many of these faults are reactivated normal faults from one branch of a complex Cretaceous to Paleogene rift system. Heteroaxial folding in parts of the SBS is probably due to a slight component of range-parallel dextral strike-slip motion acting on preexisting faults striking north and NE during inversion. Regional balanced cross sections along two transects across the northern SBS indicate that the major faults flatten into a detachment in the basement at about 10 km depth. Neogene E-W contraction in the SBS is of the order of 21–26 km. Rift extension is not very well constrained but was probably less than 10 km. The structural style of the SBS differs from the thin-skinned Subandean thrust belt to the north and from the large-wavelength Sierras Pampeanas basement uplifts to the south. The changes between the different styles are sharp and coincide with the northern and southern boundaries of the rift in the foreland, suggesting that crustal or lithospheric heterogeneities exert an overriding control on foreland structural style. *INDEX TERMS:* 8010 Structural Geology: Fractures and faults; 8015 Structural Geology: Local crustal structure; 8102 Tectonophysics: Continental contractional orogenic belts; 9360 Information Related to Geographic Region: South America; *KEYWORDS:* central Andes, Subandean zone, Salta rift, fault reactivation, flat subduction. **Citation:** Kley, J., and C. R. Monaldi, Tectonic inversion in the Santa Barbara System of the central Andean foreland thrust belt, northwestern Argentina, *Tectonics*, *21*(6), 1061, doi:10.1029/2002TC902003, 2002.

1. Introduction

[2] Fold and thrust structures of Neogene age form the eastern to northeastern slopes of the entire central Andes. A pronounced along-strike segmentation of this foreland thrust belt in terms of structural style was noted early on and led to the definition of different geologic provinces or segments. In southern Bolivia and northwestern Argentina these segments are, from north to south, the Subandean Ranges, the Santa Barbara System, and the Sierras Pampeanas (Figure 1). The Subandean Ranges to the north are a thin-skinned fold and thrust belt detached in a regional Silurian shale unit [*Allmendinger et al.*, 1983; *Aramayo Flores*, 1989; *Baby et al.*, 1989, 1992; *Dunn et al.*, 1995; *Mingramm et al.*, 1979], whereas the Sierras Pampeanas to the south are an extensive province of large basement uplifts associated with deep reaching thrust or reverse faults [*González Bonorino*, 1950; *Jordan and Allmendinger*, 1986]. The Santa Barbara System was originally considered part of the Subandean Ranges [*Bonarelli*, 1913], but was later defined as an independent geological unit essentially for two reasons [*Baldis et al.*, 1976; *Rolleri*, 1976]: first, the presence of a thick sequence of predominantly continental Cretaceous strata, later interpreted as rift and post-rift sequences, and secondly, a basement-involved structural style, where Ordovician to Precambrian units are exposed in the hanging walls of thrust faults. Various authors have shown that many thrust faults of the Santa Barbara System are reactivated normal faults of the Cretaceous rift [*Bianucci et al.*, 1982; *Cristallini et al.*, 1997; *Grier et al.*, 1991; *Kress*, 1995; *Salfity et al.*, 1993].

[3] The structural segmentation of the South American plate in the Andes coincides in part with the segmentation of the subducting Nazca plate in nearly horizontal and more steeply dipping portions [*Barazangi and Isacks*, 1976; *Pilger*, 1981]. This was interpreted to indicate a direct control of subduction geometry on the mode of upper plate deformation. In particular, thick-skinned thrusting was thought to be triggered by subhorizontal subduction underneath [*Jordan et al.*, 1983]. However, foreland segmentation in the Andes also reflects inherited stratigraphic and structural inhomogeneities of the South American margin [*Allmendinger et al.*, 1983; *Kley et al.*, 1999; *Mpodozis and Ramos*, 1989]. The Santa Barbara System overlies the transition in the Nazca plate from a 25–30° dip under the Subandean Ranges to a subhorizontal dip under the Sierras Pampeanas [*Cahill and Isacks*, 1992]. It is therefore in a critical region for assessing the influence of subduction geometry on foreland structural style.

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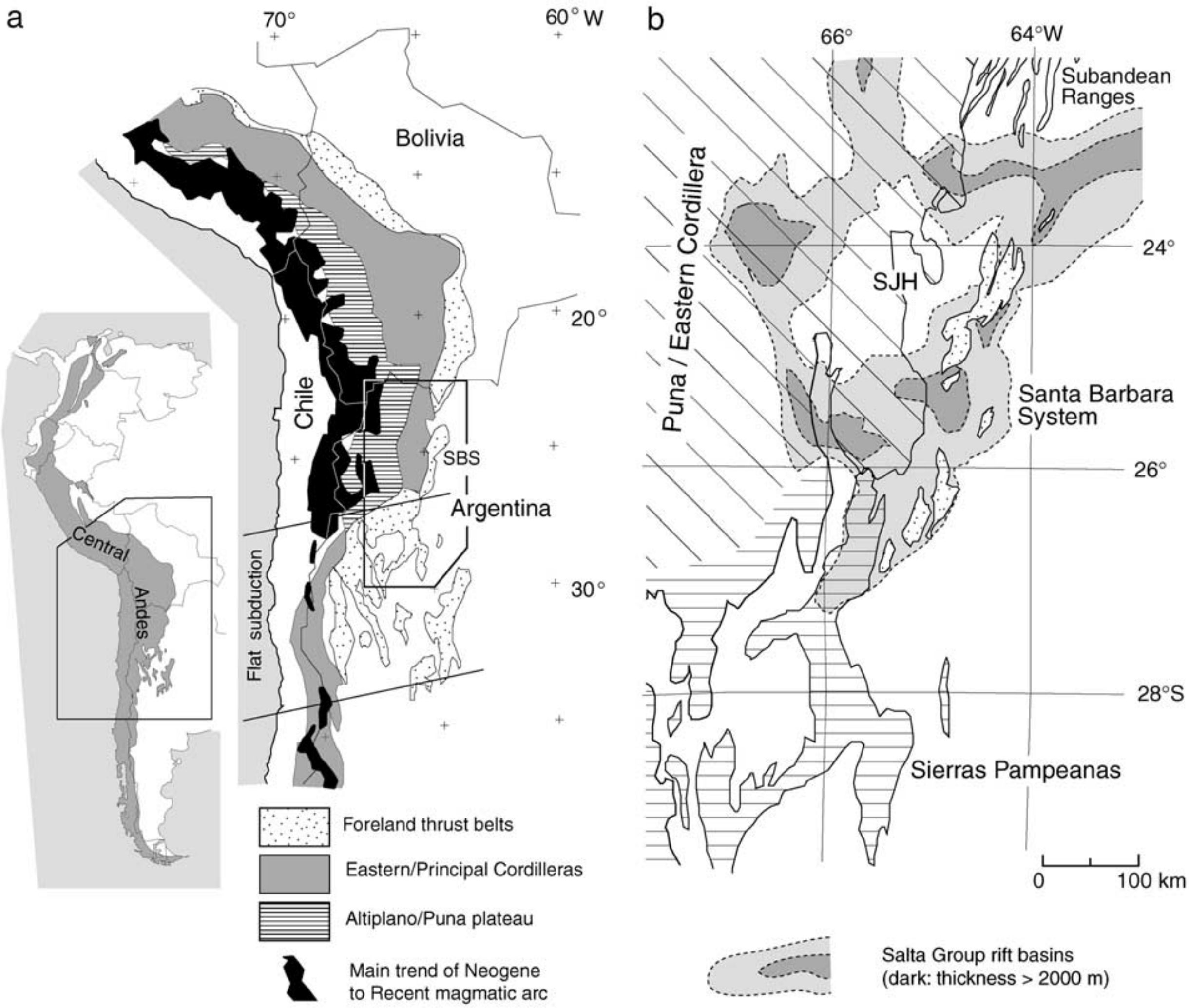


Figure 1. (a) Location of the Santa Barbara System. (b) Its relation to adjacent foreland segments (Subandean Ranges, open; Sierras Pampeanas, horizontal ruling) and the Cretaceous to Paleogene Salta Group rift. SJH, Salta-Jujuy high.

[4] In this paper we present the results of structural fieldwork focused along two transects across the Santa Barbara System. The new data are summarized and interpreted in regional cross sections. We derive amounts of orogenic contraction and earlier extension in the inverted rift system and discuss its kinematic links with the high Andes and other foreland segments along strike.

2. Stratigraphy and Geologic Evolution

[5] The stratigraphic succession of the Santa Barbara System comprises four major sequences (Figure 2): (1) A basement of Late Proterozoic to Middle Cambrian low grade metasedimentary rocks and granitoids is overlain with a regional angular unconformity by (2) a series of marine siliciclastic sediments of Late Cambrian through Devonian age. These are disconformably overlain by (3) a predominantly continental succession of red beds with minor limestone intercalations (Salta Group). The Salta Group strata are capped by (4) a thick continental foreland basin fill that was shed from the rising Andes in the west in Late Oligocene or Early Miocene to Recent time.

[6] The metasedimentary basement rocks are tightly to isoclinally folded. They grade from very low grade metamorphic slates and sandstones in the north to low grade schists and psammites in the south [*Willner et al.*, 1987]. Their original thickness is estimated at several kilometers.

[7] The unconformably overlying Upper Cambrian to Devonian succession consists of marine quartzites, sandstones and shales with a maximum cumulative thickness of some 4000 m. Despite the presence of thick shale horizons no regional detachments have formed in the Santa Barbara System in this succession.

[8] The rift-related Cretaceous to Paleogene Salta Group (reviewed by *Salfity and Marquillas* [1994]) disconformably overlies Lower Paleozoic strata in the northern Santa

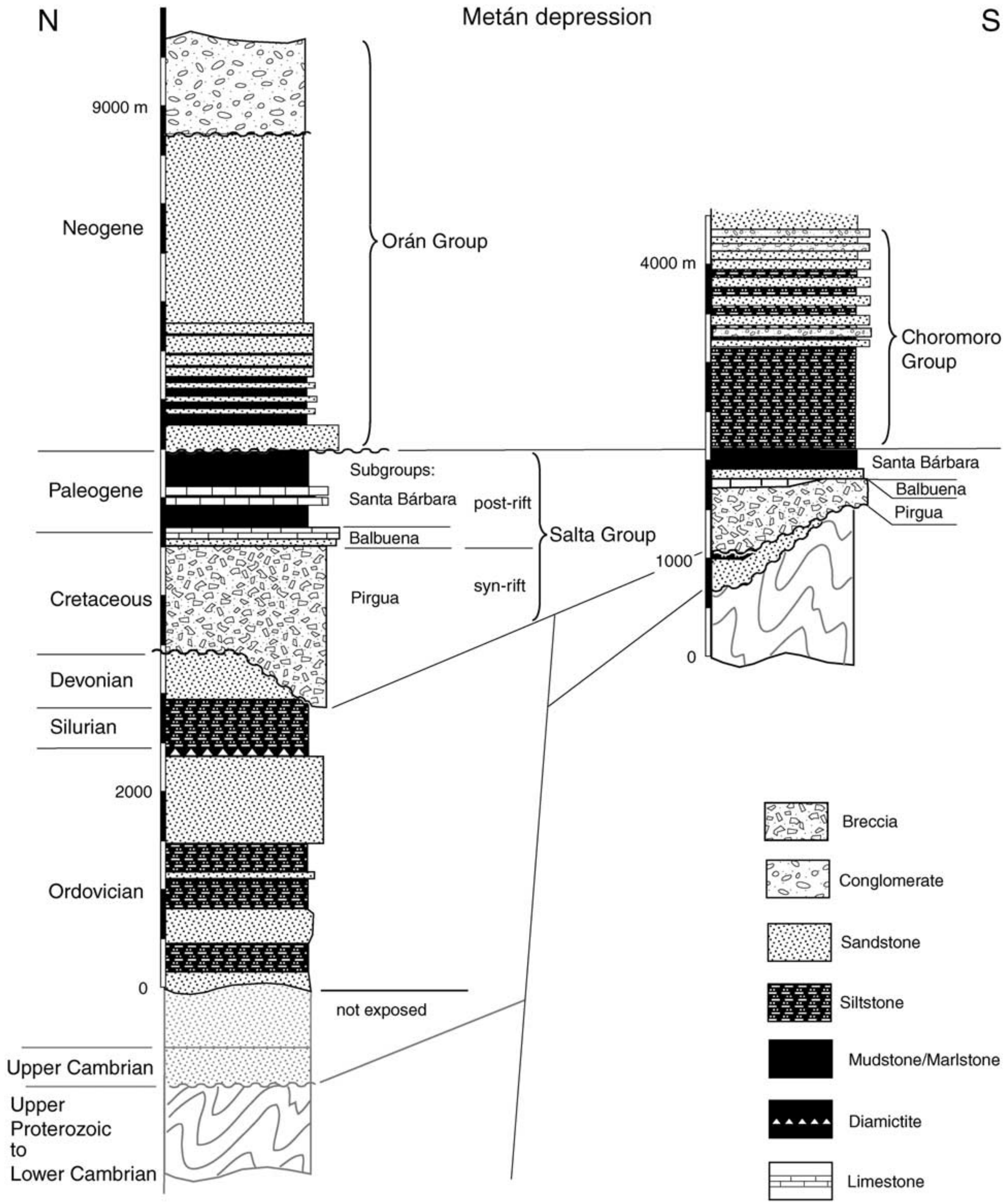
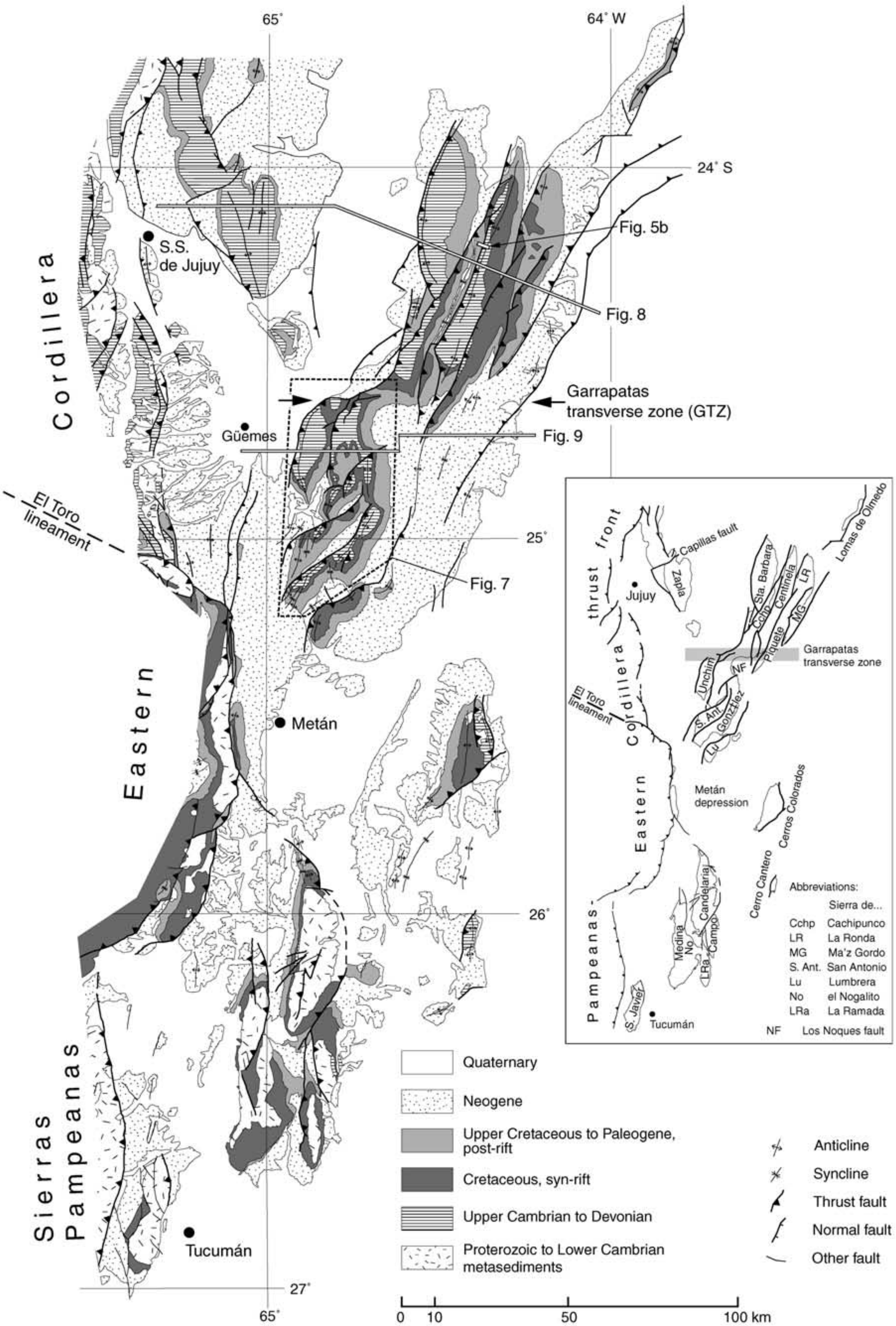


Figure 2. Stratigraphic columns of the Santa Barbara System north and south of the Metán depression (Figure 3, inset). Southern column after data from *González and Mon* [1996].

Barbara System and Upper Proterozoic strata in the south. No angular unconformity is visible on outcrop scale between the Paleozoic and Cretaceous rocks. The Salta Group is subdivided from bottom to top in the Pirgua, Balbuena and Santa Barbara subgroups [*Salfity and Marquillas*, 1994]. The Early to Late Cretaceous Pirgua subgroup consists mainly of red continental conglomerates and sandstones and has some intercalated alkaline volcanics



65°
64° W
24° S
25°
26°
27°
65°
S.S. de Jujuy
Fig. 5b
Fig. 8
Garrapatas transverse zone (GTZ)
Güemes
Fig. 9
El Toro lineament
Fig. 7
Metán
Tucumán
Cordillera
Eastern
Sierras Pampeanas
thrust front
Capillas fault
Zapla
Jujuy
Lomas de Olmedo
Sta. Barbara
Centinela
LR
Cchp
MG
Piquete
Garrapatas transverse zone
Unchim
NF
S. Ant.
González
Lu
Eastern Cordillera
Metán depression
Cerros Colorados
Cerro Cantero
Candelaria
Medina
No
Campo
LRa
Pampeanas
S. Javier
Abbreviations:
Sierra de...
Cchp Cachipunco
LR La Ronda
MG Ma'z Gordo
S. Ant. San Antonio
Lu Lumbrera
No el Nogalito
LRa La Ramada
NF Los Noques fault
Quaternary
Neogene
Upper Cretaceous to Paleogene, post-rift
Cretaceous, syn-rift
Upper Cambrian to Devonian
Proterozoic to Lower Cambrian metasediments
Anticline
Syncline
Thrust fault
Normal fault
Other fault
0 10 50 100 km

[*Galliski and Viramonte*, 1988]; it is considered to represent the syn-rift stage. The maximum thickness of syn-rift strata in the Santa Barbara System is about 2000 m. The Latest Cretaceous to Early Paleocene Balbuena subgroup comprises sandstones and limestones deposited in continental to restricted marine environments and some shales in more strongly subsiding parts of the basin. The Paleocene to Early Eocene Santa Barbara subgroup is dominantly shaly with a few carbonate intercalations. The Balbuena and Santa Barbara subgroups are thought to represent the post-rift thermal subsidence stage, although some normal fault activity and minor basalt intercalations have been documented [*Bianucci et al.*, 1982]. The post-rift succession attains a maximum thickness of some 900 m in the Santa Barbara System.

[9] A thick succession of clastic, mostly continental foreland basin strata was deposited from about 15 Ma onward in the area of the Santa Barbara System. These strata exhibit a general coarsening upward trend. They reach a maximum thickness of about 4000 m in the northern Santa Barbara System but thin to the south.

[10] The main deformation of both the Santa Barbara System and the Zapla anticline postdates the deposition of much of the foredeep succession and is therefore younger than 5 Ma [*Reynolds et al.*, 1994, 2000]. A first subtle inversion of the Salta Group rift was interpreted to have occurred after the deposition of the Santa Barbara subgroup and before the deposition of foreland basin strata [*Salfity et al.*, 1993], i.e., between about 50 Ma and 15 Ma.

3. Structure

3.1. Regional Structure

[11] The Santa Barbara System comprises an array of north to NNE trending anticlines, many of them associated with thrust or reverse faults. Most anticlines cluster in two large bundles separated by the Metán depression while a few smaller, isolated anticlines lie along the eastern margin of the Santa Barbara System (Figure 3). The two segments north and south of the depression differ in some stratigraphic and structural aspects (Figures 2 and 3): north of the Metán depression, the oldest strata exposed are Ordovician, whereas older units of Proterozoic and locally Cambrian age crop out in the south. This pattern reflects the changing stratigraphic position of the base Cretaceous unconformity which cuts into older strata southward across the pre-Cretaceous El Toro fault zone. Regarding structure, there are more emergent thrusts in the northern segment and they are consistently west vergent. In the southern segment the folds are gentler and the few emergent thrusts are both east and west directed. In this paper, we will focus on the northern segment, but occasionally refer to the southern segment as well. For more information on the southern segment, the reader is referred to *Mon* [1971, 1972], *Mon and Dinkel* [1974], and *González and Mon* [1996]. The gentle structures underlying the Metán depression are shown in a cross section by *Grier et al.* [1991] and interpreted in more detail by *Cristallini et al.* [1997].

[12] The large-scale structure of the northern segment is characterized by a series of north to NNE striking fold-thrust structures which are separated from the Eastern Cordillera by the broad synclinal Lavayén valley. The individual anticlines are asymmetric toward the west, with gently dipping, long, planar back limbs and steeply dipping to overturned front limbs. The front limbs are typically cut by east dipping thrust or reverse faults. These major faults are rarely exposed in the densely vegetated area, but most of them appear to dip steeply at shallow levels and have high cutoff angles (Figure 4). Fault displacements are highest on the westernmost faults and diminish toward the east. Many faults are strongly curved in map view and tend to abut against other faults at high angles. Regional west dipping reverse faults, exposed and imaged on seismic lines [*Bianucci et al.*, 1982], are present only along the eastern margin of the northern segment and have limited throw and topographic expression. The northern segment is further subdivided along strike by the prominent E–W trending Garrapatas transverse zone (GTZ) [*Monaldi and Kley*, 1997]. Across this element, the entire bundle of fold-thrust structures steps about 15 km to the right. South of the GTZ the folds and thrusts are arranged less regularly than to the north. Oblique structures are more frequent, and shorter wavelength folds, in part with mutually orthogonal contraction directions, occur locally.

[13] Sierra de Zapla is a large anticline that trends SSE, away from the front of the Eastern Cordillera, and plunges in SSE direction under the Lavayén valley. The Zapla anticline is considerably wider than any fold in the Santa Barbara System. Its vergence is toward the SW. Both limbs of the Zapla anticline are cut by reverse faults which dip toward its core. The fault along the SW margin, although poorly exposed, appears to be more important.

3.2. Normal Fault Reactivation

[14] Evidence that some of the principal thrust faults in the Santa Barbara System are reactivated Cretaceous normal faults can be found on quite different scales. On a regional scale, the almost perfect alignment of the Neogene contraction structures with one of the subbasins of the Salta group rift is conspicuous (Figure 1b). However, it is interesting to note that the most intensely structured areas of the Santa Barbara System do not coincide with the maximum thicknesses of syn-rift strata; rather, faulting is concentrated along the rift borders. This is particularly evident for the Metán depression, but also north of the GTZ where the Santa Barbara thrust carries no syn-rift strata in its hanging

Figure 3. (opposite) Geologic map of the Santa Barbara System, simplified and modified from *Mon* [1971, 1972], *Mon and Dinkel* [1974], *González and Mon* [1996], *Servicio Geológico Argentino* [1996] and *Salfity et al.* [1998]. Locations of Figures 5b, 7, 8 and 9 are shown. Inset shows the names of important topographic and structural elements. Major faults are named after the mountain ranges they bound.

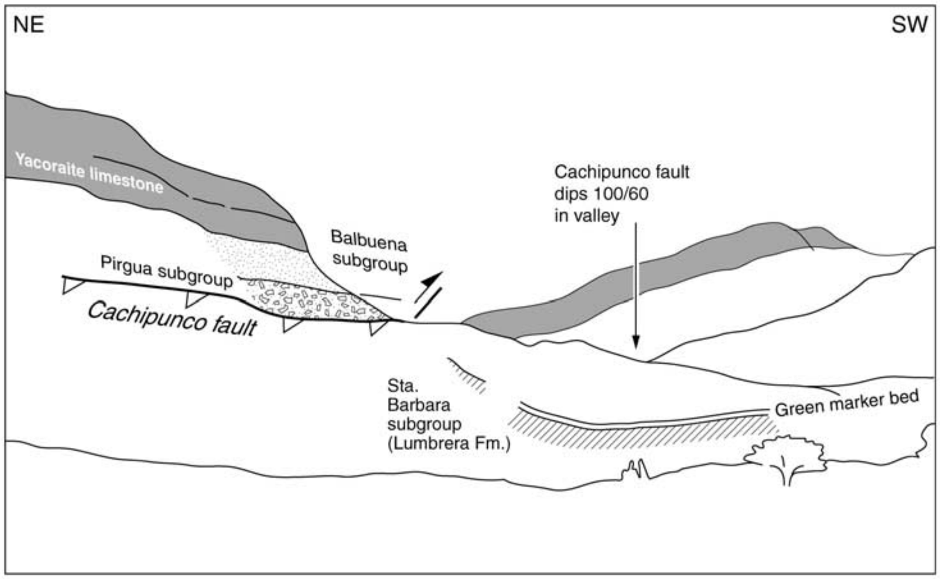


Figure 4. Field aspect of the Cachipunco thrust, an inverted Cretaceous normal fault (compare Figure 5c). Drawn after photograph. Notice steep surface dip of the fault and gentle footwall syncline.

wall, indicating that it had no significant normal movement prior to thrusting.

[15] At the level of major structures two of the principal faults reverse their sense of stratigraphic separation along strike, from thrust at their tips to zero or slightly normal in their central segments (Figure 5a). This indicates the existence of null points, where the initial normal offset equals the amount of later reverse movement. Rapid thickness and facies changes of the Cretaceous syn-rift succession across present-day reverse faults have been documented in the field [*Salfity et al.*,1993], (Figure 5b) and from reflection seismic data on subsurface structures at the northern end of the Santa Barbara System [*Bianucci et al.*, 1982], also reproduced by *Lowell* [1995]. The inverted normal faults imaged on the seismic lines continue to the south along the eastern margin of the Santa Barbara System. In one locality on the Centinela thrust, a normal fault segment appears to be preserved in the hanging wall of the contractional fault (Figure 5c), suggesting a "footwall shortcut" thrust that has splayed from a listric normal fault during inversion.

3.3. Range-Parallel Strike-Slip Motion

[16] A dextral strike-slip component of movement along faults of the northernmost Santa Barbara System was first interpreted by *Bianucci et al.* [1982] from the orientation of folds and subsidiary faults which form acute angles with the main faults in the Olmedo branch of the rift basin. The general shortening direction in the Andean foreland of northernmost Argentina is assumed to be W-E to WNW-ESE from regional structures and kinematic analysis of faults [*Marrett et al.*, 1994]. Since the faults in the Olmedo area trend NE as compared to north to NNE in most of the Santa Barbara System, this is where a strike-slip component would be expected to be most pronounced. However, we also found evidence for dextral strike-slip along the more northerly trending faults farther south. In particular, folds at scales from centimeters to tens of meters with steeply plunging axes and asymmetry suggesting dextral motion were observed at several localities in the vicinity of the major reverse faults (Figure 6). In some cases the steep axes could also have formed in a different way, e.g., by later rotation of horizontal or gently plunging fold axes. In other cases, such as the folding of steeply dipping cleavage planes in gently dipping beds (Figure 6b), the evidence for strike-slip motion seems unequivocal. We cannot quantify the amounts of strike-slip displacements, but given the small scale of the observed structures we assume that it is subordinate compared to the reverse motion.

3.4. Transverse and Oblique Structures

[17] Apart from the presumably small strike-slip component superimposed on the reverse movement of the major faults, strike separations also occur across a number of relatively large faults trending NW, NE, and east. The most conspicuous NW trending structure occurs at the southern terminations of the Unchimé and San Antonio anticlines where the plunging folds swing abruptly from north into NW trend (Figure 7). In addition, the two NW trending fold segments are perfectly aligned with each other (marked by an arrow in Figure 7b), possibly indicating that they overlie a single deeper NW trending fault. Major NE trending faults are the Capillas fault which dissects the Zapla anticline and the Los Noques fault in the Santa Barbara System (Figure 3, inset). Striations on exposed parts of the Capillas fault indicate top to the SE reverse motion, suggesting that the considerable sinistral offset it has caused in the SW limb of Zapla anticline is not due to strike displacement but to vertical offset of the dipping fold limb.

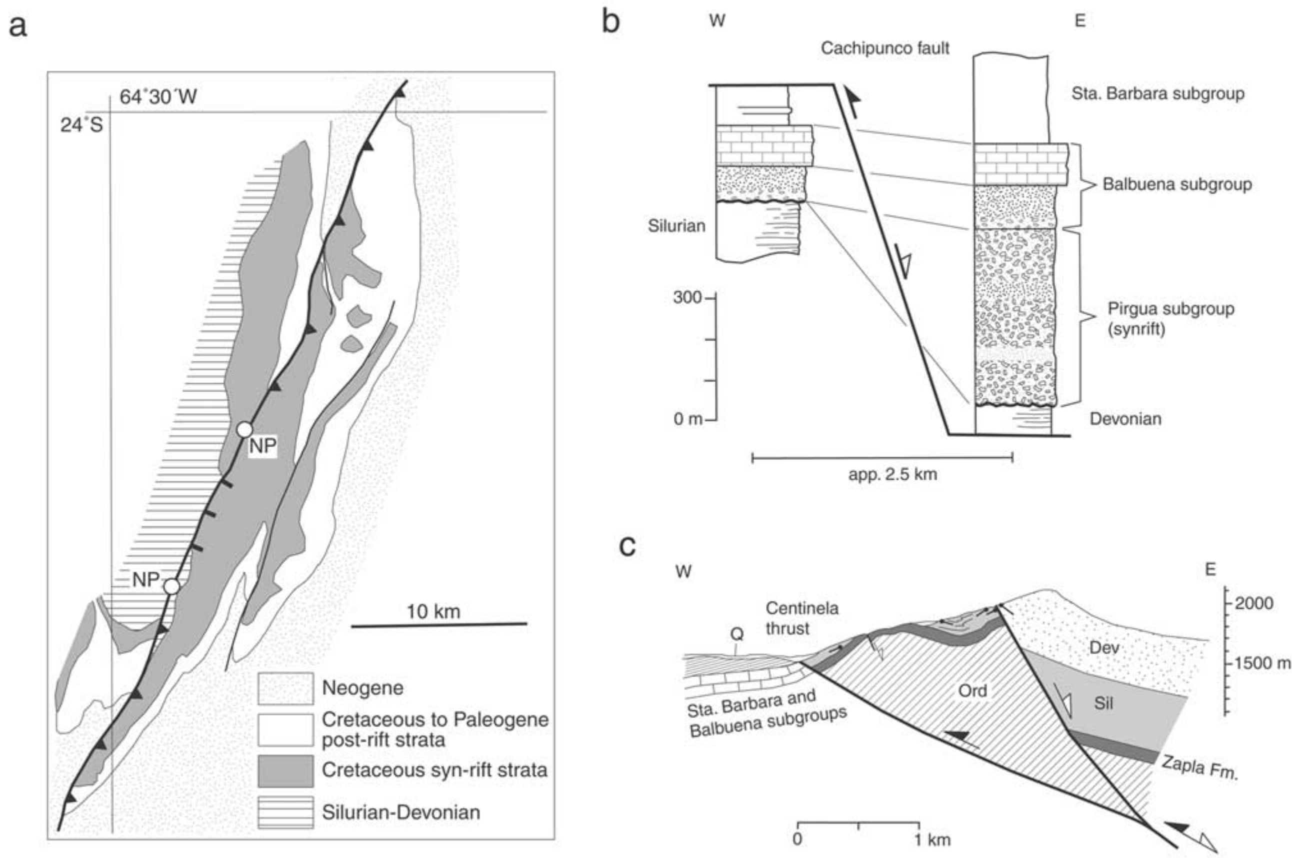


Figure 5. Evidence for normal fault reactivation at different scales. (a) Reversed sense of movement along the Piquete fault from thrust near tips to normal at center. NP: Null points where amount of reverse movement equals original normal displacement. (b) Rapid decrease in syn-rift strata thickness from a few hundred meters to zero across the Cachipunco fault. (c) Sketch section across the Centinela thrust, located in Figure 3. Stratigraphic and structural relations suggest a normal fault segment carried passively in the hanging wall.

[18] The most pronounced east trending structure is the rather diffuse Garrapatas transverse zone (GTZ) which comprises a series of aligned fold and fault terminations as well as some discrete but short east trending faults. Of the major reverse faults, only one can be traced across the GTZ, while the others die out and are replaced by new ones. Clearly discernible east trending folds only occur in a limited area south of the GTZ where they interfere with north trending folds to form small domes and basins (Figure 7). All oblique and transverse faults appear to have a component of N-S contraction.

3.5. Regional Cross Sections

[19] In order to extrapolate the near-surface structures to depth, to determine depths to detachment and to estimate the amount of shortening accommodated in the Santa Barbara System we constructed two regional balanced cross sections located north and south of the GTZ (Figure 8). The northern section comprises the Zapla anticline, the Lavayén Valley and the Santa Barbara System, whereas the southern section only comprises the Santa Barbara System. The cross sections are based entirely on geological surface data in the areas of high topographic relief, but a few industrial seismic lines were available to constrain the structural interpretation beneath the lowlands. The seismic lines resolve the structure fairly well down to a prominent reflector formed by the Yacoraite limestones near the base of the post-rift succession (Figures 2 and 4); this corresponds to a maximum depth of some 4 km. Beyond, they provide little constraint for the structural interpretation. The extent of seismic coverage is marked in Figures 8 and 9.

[20] The fault displacements are not very well constrained in some cases where the base of the Cretaceous syn-rift strata is not exposed and their full thickness is unknown. For those faults we used minimum estimates. The most important constraints on the deep geometry of the faults are their low displacements of a few kilometers at most, their high cutoff angles at the surface and the long wavelength of the hanging wall anticlines, which together imply a deep basal detachment level. As pointed out above, narrower folds suggesting the existence of secondary, shallower

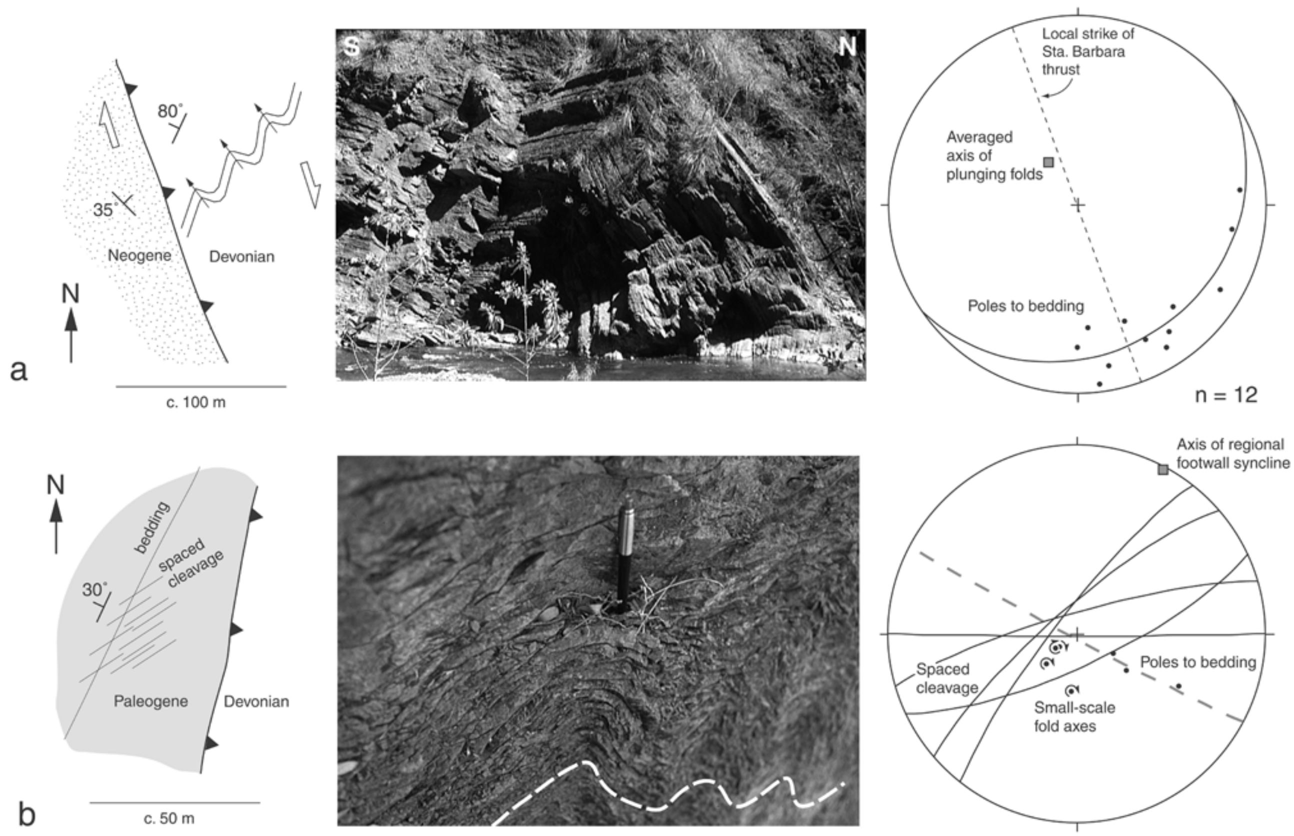


Figure 6. Indicators of dextral strike slip motion at different scales. (a) Sketch of outcrop situation (left), photograph of plunging fold in Devonian sandstones (middle; field of view c. 10 m across), and equal-area stereoplot of poles to bedding with averaged fold axis (right). Hanging wall of Santa Barbara thrust. (b) Spaced cleavage folded into Z-shaped folds with steeply plunging axes. Outcrop situation (left), photograph (middle), and stereoplot (right). View in photograph is from above, pen is about vertical. Equal-area stereoplot shows orientation of spaced cleavage and fold axes relative to regional structure. Footwall of Cachipunco fault.

detachment levels are rare. The planar backlimbs of the large anticlines are most easily explained as resulting from rotation over listric, approximately circular faults [cf. *González Bonorino*, 1950; *Erslev*, 1986]; they are too long to be produced by movement over planar ramps with the fault displacements available. Together with the curved traces in plan view this suggests an overall spoon shape for many faults.

[21] The cross sections were constructed with the basal detachment as shallow as possible, corresponding to about 10 km depth for both cross sections. Although the thickness of basal Ordovician and Upper Cambrian strata and hence the depth to the basement are not well known, this estimate for the detachment level implies that the faults sole in Cambrian/Precambrian metamorphic basement. The poorly constrained depth to the basement/cover interface poses problems for the extrapolation of structures to depth and section balancing. In the sedimentary cover the line lengths of stratigraphic contacts could be balanced. The basement, though only exposed south of the Metán depression, probably consists of low-grade clastic metasediments and possibly a few granitoid intrusions throughout the Santa Barbara System. Just how the already tightly folded and often steeply dipping metasediments accommodated the additional Tertiary folding is not clear. Distributed slip on bedding and cleavage planes was probably important. At any rate, field observations in the Eastern Cordillera show that the basement/cover contact, though strongly unconformable, is not a mechanical discontinuity but is folded parallel to bedding in the sedimentary cover. We therefore took a simplified approach, drawing auxiliary lines at regular 1-km spacing parallel to a datum horizon in the Cretaceous succession and balancing the lengths of these auxiliary lines at deeper levels, thus conserving area. Deep, poorly known stratigraphic contacts were treated as mere passive markers. Internal deformation of the thrust sheets is by simple shear parallel to the auxiliary lines. The strike-slip component of the faults, as discussed above, is probably small compared to the thrust or reverse component. It was therefore neglected when constructing the cross sections.

[22] The most ambiguous part in terms of structural extrapolation is the wide and gentle Lavayén valley syncline. The cross-sectional areas raised above the regional elevation are very large on both limbs, whereas shortening

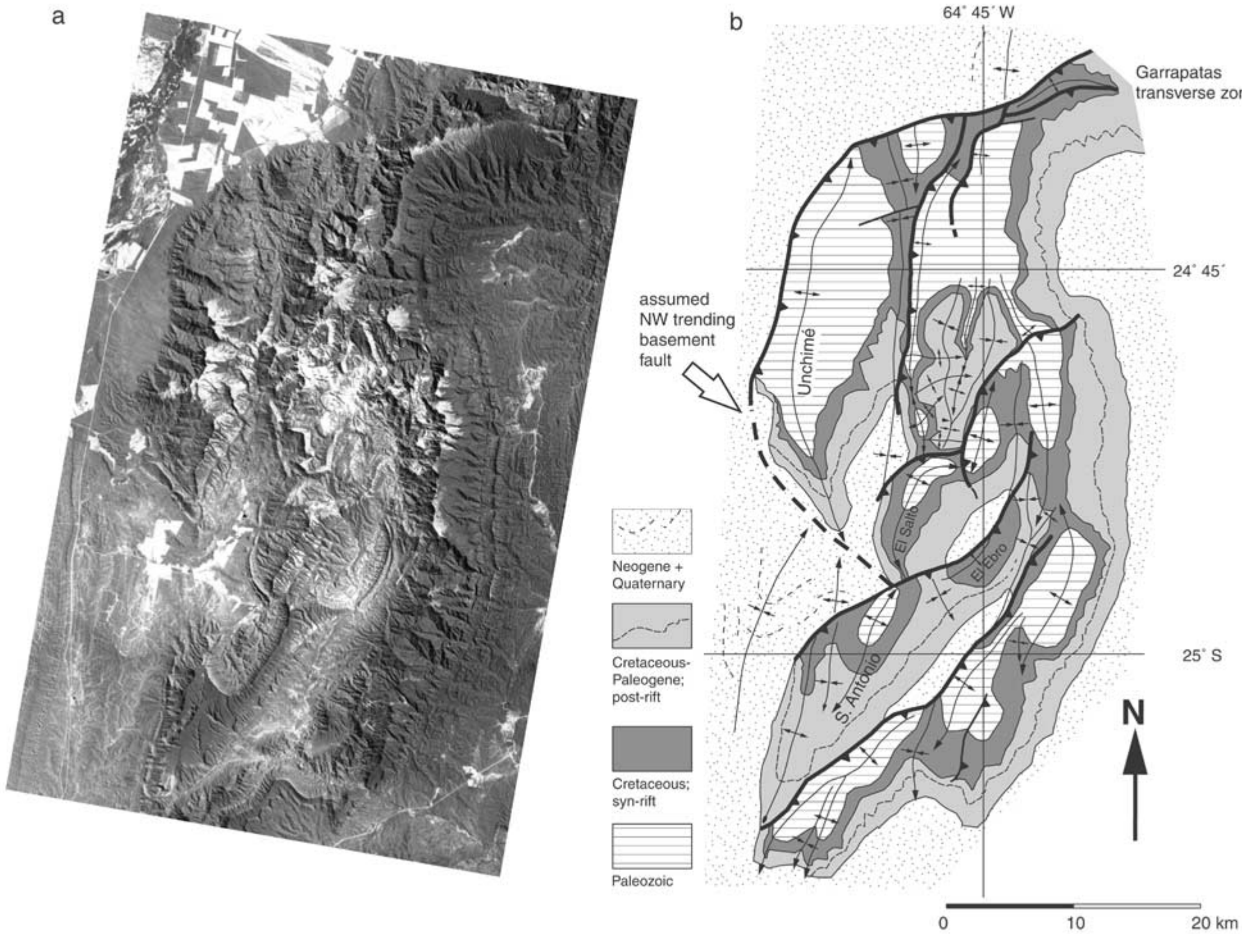


Figure 7. (a) Detail of Landsat TM scene (location in Figure 3) of the area between the Garrapatas transverse zone and the Metán depression. (b) Structural interpretation. Structures referred to in the text are labeled. Notice heteroaxial folding in the central part of the map.

of the syncline by folding alone is near zero. This problem can be solved in two ways: First, wedge-shaped thrust stacks with a "triangle zone" or "passive roof" geometry could underlie the limbs of the syncline. This would require the displacement from the thrust stack to be transferred to bedding parallel back thrusts. The Santa Barbara thrust would then have to be a late fault which dissects the earlier formed thrust stack and the backthrust. However, the only known example of passive backthrusting in the Santa Barbara System appears to be the SE verging thrust associated with the Olmedo anticline (Figure 3) [*Kress*, 1995; *Bianucci*, 1999]. In particular, there is no evidence for an east directed back thrust splaying from the crest of the Santa Barbara anticline where it terminates in the north. Alternatively, the flanks of the Lavayén syncline can be modeled as backlimbs of large ramp anticlines. This solution was used in the cross sections. In the northern section which runs right across the Lavayén syncline, a long, gently west dipping ramp was assumed to connect the deep detachment under the Zapla anticline with the shallower detachment under the Santa Barbara System. The eastward displacement on this stepped thrust is accommodated by the west verging backthrusts of the Santa Barbara System. The amount of shortening on these faults independently constrains the large ramp to be located correctly under the east limb of the Lavayén syncline. The cross sections as shown yield shortening values of 6 km for the Zapla anticline and of about 20 to 25 km for the Santa Barbara System.

3.6. Map View Kinematics

[23] The kinematic links of the strike slip components on the major reverse faults and the movements on the oblique and transverse structures with the dominant E-W to WNW-ESE contraction cannot be analyzed in two dimensions. In particular the structures suggesting N-S contraction raise the question if the entire structural inventory can be explained in the framework of a single deformation event or if distinct, non-coaxial deformation phases must be invoked. Rapid changes of faulting regimes during the last 10–5 Ma have been documented in the Puna, the Eastern Cordillera and the westernmost Sierras Pampeanas [*Allmendinger*, 1986; *Grier et al.*, 1991; *Marrett and Strecker*, 2000; *Marrett et al.*,

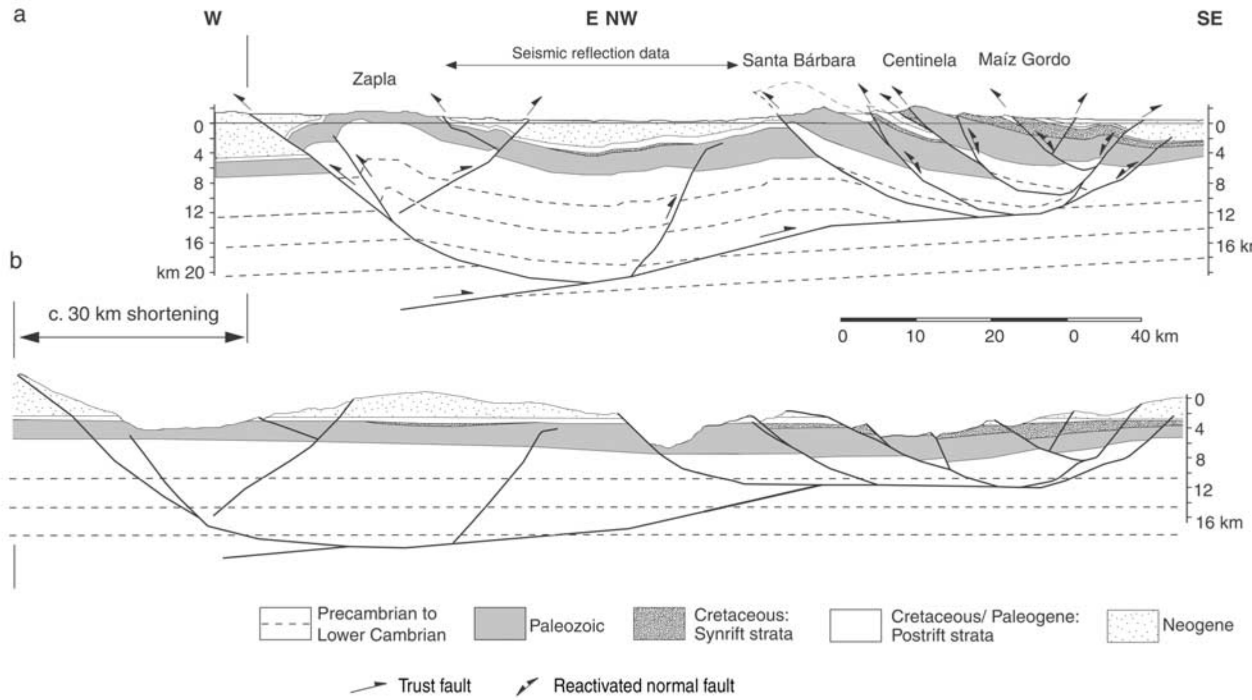


Figure 8. Cross section of the Santa Barbara System north of the Garrapatas transverse zone. Location in Figure 3. (a) Present-day. (b) Neogene inversion restored. Dashed lines are auxiliary lines explained in text.

1994], but never in the low-lying Subandean foreland. In contrast to the Eastern Cordillera, there are no clear and consistent crosscutting relationships between structures of different orientation in the Santa Barbara System and no relative chronology can be established. This is particularly evident between the GTZ and the Metán depression where fold and fault orientations are highly variable (Figure 7). For example, the southern end of the El Salto anticline is clearly

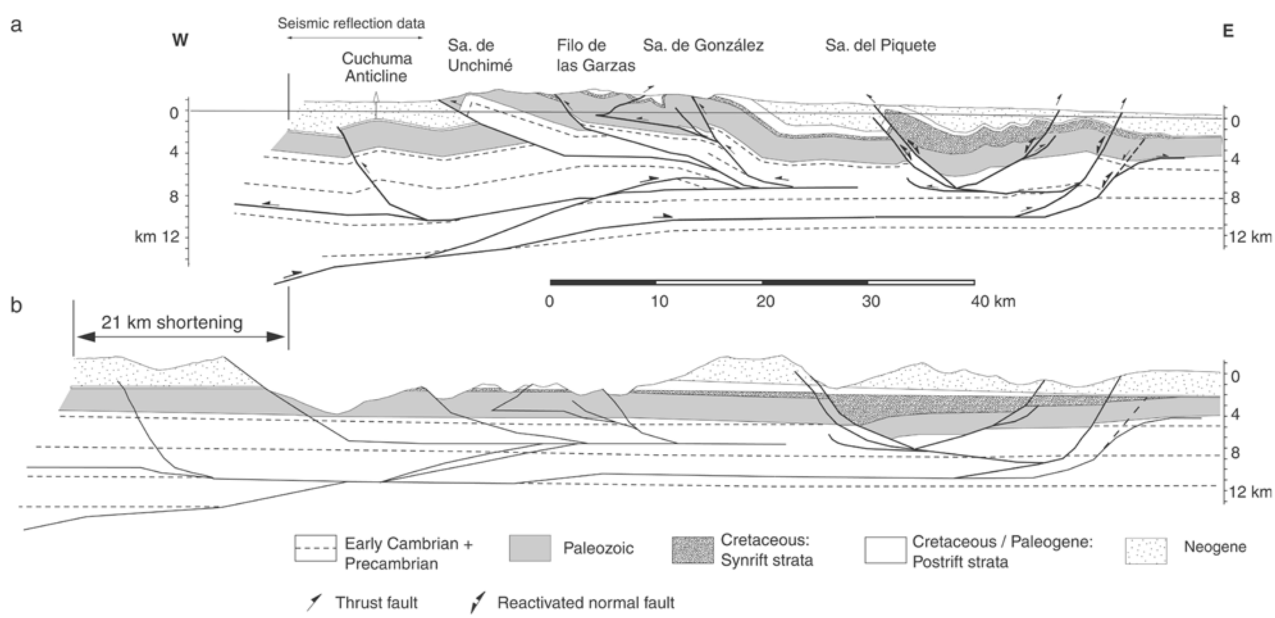


Figure 9. Cross sections of the Santa Barbara System between the Garrapatas transverse zone and the Metán depression. Location in Figure 3. (a) Present-day. (b) Neogene inversion restored. Dashed lines are auxiliary lines explained in text.

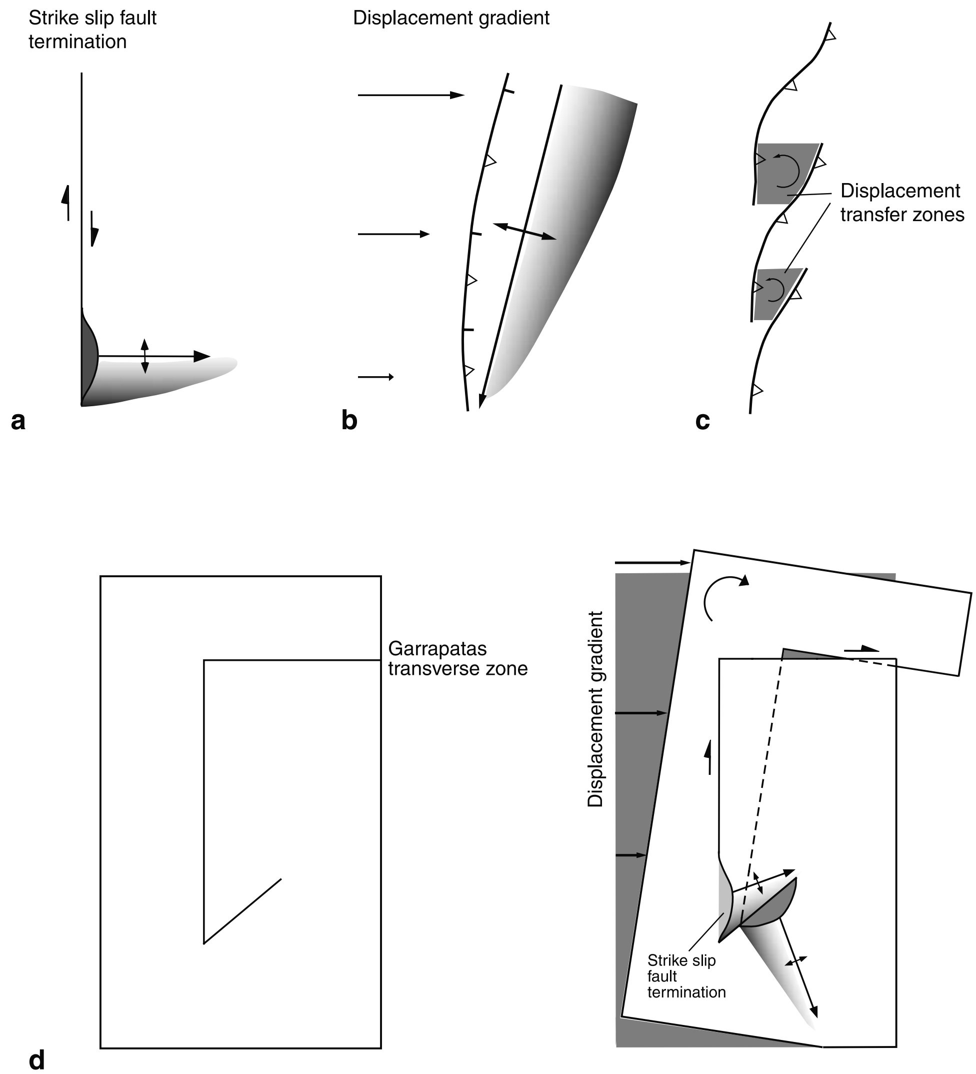


Figure 10. Interpreted components of the kinematic pattern south of the Garrapatas transverse zone. (a) southward termination of dextral strike slip fault creates E-W trending folds. (b) N-S displacement gradient rotates fold axes clockwise with respect to displacement vectors. (c) Displacement transfer between pre-existing(?) en echelon faults. (d) Simplified cut paper model demonstrates orthogonal fold trends created by combination of (a) and (b).

cut by the San Antonio/El Ebro thrust, but the anticline does not continue in its hanging wall. This suggests that the San Antonio fault existed before the El Salto anticline but also moved while or after the anticline formed. Another conspicuous structural feature south of the GTZ is the en echelon arrangement of regional NE trending thrusts that die out toward the NE in the same, easternmost anticline.

[24] The variably trending faults and folds appear to accommodate three different components of the overall kinematics that exist besides the dominant E-W contraction (Figures 10a–10c): (1) the southern termination of dextral strike slip produces east to NE trending structures, (2) displacement is transferred between NE trending thrust faults and (3) the magnitude of E-W contraction diminishing southward produces an overall southward plunge and rotates the local shortening axes to a SE direction [cf. *Hindle et al.*, 2000]. Inherited NE trending faults have very likely conditioned the en echelon fault system and enhanced the rotation caused by the displacement gradient. Figure 10d shows a strongly simplified geometric model of how the observed fault and fold directions south of the GTZ might fit into a frame of dextral transpression interacting with preexisting faults of north and NE trends. The complex structure could thus be explained in terms of regional E-W shortening alone, although we cannot exclude other scenarios with changing shortening directions.

4. Crustal and Lithospheric Characteristics

4.1. Present-Day Situation

[25] The present-day crustal and lithospheric properties of the Andean foreland in the Santa Barbara segment are most likely determined by the combined effects of Creta-

ceous rifting with subsequent thermal subsidence and of Neogene contraction. The present-day Moho geometry was derived from seismological studies [*Whitman*, 1994] and gravimetric modeling [*Kress*, 1995]. The Moho dips very gently westward beneath the eastern parts of the Santa Barbara System but steepens to as much as 15° westward dip under the western Santa Barbara System and the front of the Eastern Cordillera. Although this geometry is broadly similar to the foreland farther north, the gradients in Moho topography are steeper and the dynamic state is different: in the north, a paired isostatic anomaly coincides with the Eastern Cordillera (positive) and the Subandean region (negative). This is interpreted to reflect regional isostatic compensation of the Andes by elastic flexure of the underthrusting Brazilian shield [*Lyon-Caen et al.*, 1985]. Farther south, the paired anomaly vanishes, suggesting that the area of the Santa Barbara System approaches local isostatic equilibrium. This has been interpreted in terms of a drastic southward reduction in flexural rigidity of the foreland lithosphere [*Watts et al.*, 1995; *Whitman et al.*, 1996], but it probably also reflects the decreasing magnitude of the Andes overthrusting the craton [*Allmendinger and Zapata*, 2000]. Magnetotelluric and geomagnetic deep soundings [*Krüger*, 1994] show lower electrical resistivities of the foreland lithosphere below 10 km depth in the south, possibly indicating elevated heat flow. Both the reduced flexural rigidity and enhanced electric conductivity are probably related to a thin lithospheric mantle as indicated by strong attenuation of seismic waves [*Whitman et al.*, 1996]. Petrologic data suggest that the thinned foreland lithosphere may be a remnant of processes active during Cretaceous rifting (see below).

4.2. Properties of the Cretaceous Rift

[26] The Cretaceous rift of northwestern Argentina has a complex geometry with four branches that radiate from a central junction toward the north, ENE, south, and NW (Figure 1b) [*Salfity and Marquillas*, 1994]. At the center of the junction is the broad Salta-Jujuy structural high. Several depocenters with increased thicknesses of syn-rift strata have been identified within this basin system. Important volcanic intercalations are restricted to the area south of the Salta-Jujuy high. The Santa Barbara System occupies the NNE trending trough that connects the Lomas de Olmedo depocenter with the Metán depocenter along the southeastern flank of the Salta-Jujuy high and it continues southward into the southern rift branch. Our two cross sections restored to a state before Neogene contraction (Figures 8 and 9) suggest a roughly symmetrical original configuration of the Santa Barbara System rift branch. Nevertheless its crustal scale geometry was proposed to be asymmetric with a single gently SE to east dipping master fault by different authors [*Cristallini et al.*, 1997; *Kress et al.*, 1993]. Such a fault may indeed connect in the east with the subhorizontal basal detachment we infer for the Santa Barbara System. It is important to note that the gently west dipping thrust fault which we assume to link the Eastern Cordillera with the Santa Barbara System is unlikely to be the reactivated extensional master fault of the rift because its hanging wall received very little or no syn-rift sediments.

[27] Restoring the pre-contraction geometry in a second step to a pre-extension state bears many uncertainties. Not all thrust faults can be demonstrated to be reactivated normal faults and the thickness and overall geometry of syn-rift strata are poorly constrained in places. However, high values of crustal extension appear unlikely. The restorations shown in Figure 11 are based on the simplified assumptions that fault geometries were the same during extension and contraction, and that the basement-involved thrust sheets essentially moved as rigid blocks (cf. *Erslev*'s [1986] model). This procedure will lead to an overestimate of the extension as compared to "inclined shear" models [*Dula*, 1991] The restored cross sections from Figures 8b and 9b were contracted and blocks were allowed to slide along the faults until all accommodation space for the Pirgua syn-rift strata was eliminated at the points where their thickness is known. Elsewhere the thickness and geometry of the Pirgua strata was adjusted to the uplift and rotations of the model blocks (Figure 11a). Large gaps and overlaps between the model blocks were minimized by simple shear deformation at varying angles, always conserving area (Figure 11b). Given the uncertainties involved, we did not attempt to reach a perfect fit. The restorations indicate an extension of 7–8 km (extension factor $\beta = 1.13$ to 1.17). This is in keeping with the low extension values derived by *Grier et al.* [1991] and *Cristallini et al.* [1997]. On the other hand, petrologic data from lower crustal xenoliths in rift related volcanics [*Lucassen et al.*, 1999] suggest strongly elevated temperatures of about 900°C at the base of the crust in Cretaceous time, probably linked with upwelling asthenosphere typical of mantle-activated rift zones. Regional isostatic compensation of the thinned lithospheric mantle may explain why the rift grabens never subsided to sea level during the rifting stage but did so during the post-rift evolution. *Lucassen et al.* [1999] argue that the strong thermal anomaly would decay slow enough to still influence the mechanical properties of the lithosphere at the onset of Neogene contraction.

4.3. Northern and Southern Boundaries of the Santa Barbara System

[28] Although the Santa Barbara System has been described as being transitional between the Subandean thin-skinned belt to the north and the Sierras Pampeanas basement uplifts to the south, there are rather sharp boundaries between the three units. In the north, the Subandean belt terminates at 23°S whereas the Santa Barbara System begins only at 23°30′S, leaving a practically undeformed swath of foreland some 60 km wide between them. This undeformed foreland region is underlain by an ENE trending branch of the Cretaceous rift, which in turn overlies a basement arch trending in the same direction (Figure 12). Before the onset of rift deposition, erosion had cut deep into the Paleozoic succession over this arch, exposing Ordovician strata along its axis [*Di Persia et al.*, 1991]. The arch may have formed due to Cretaceous thermal doming before major extension started [*Cominguez and Ramos*, 1995;

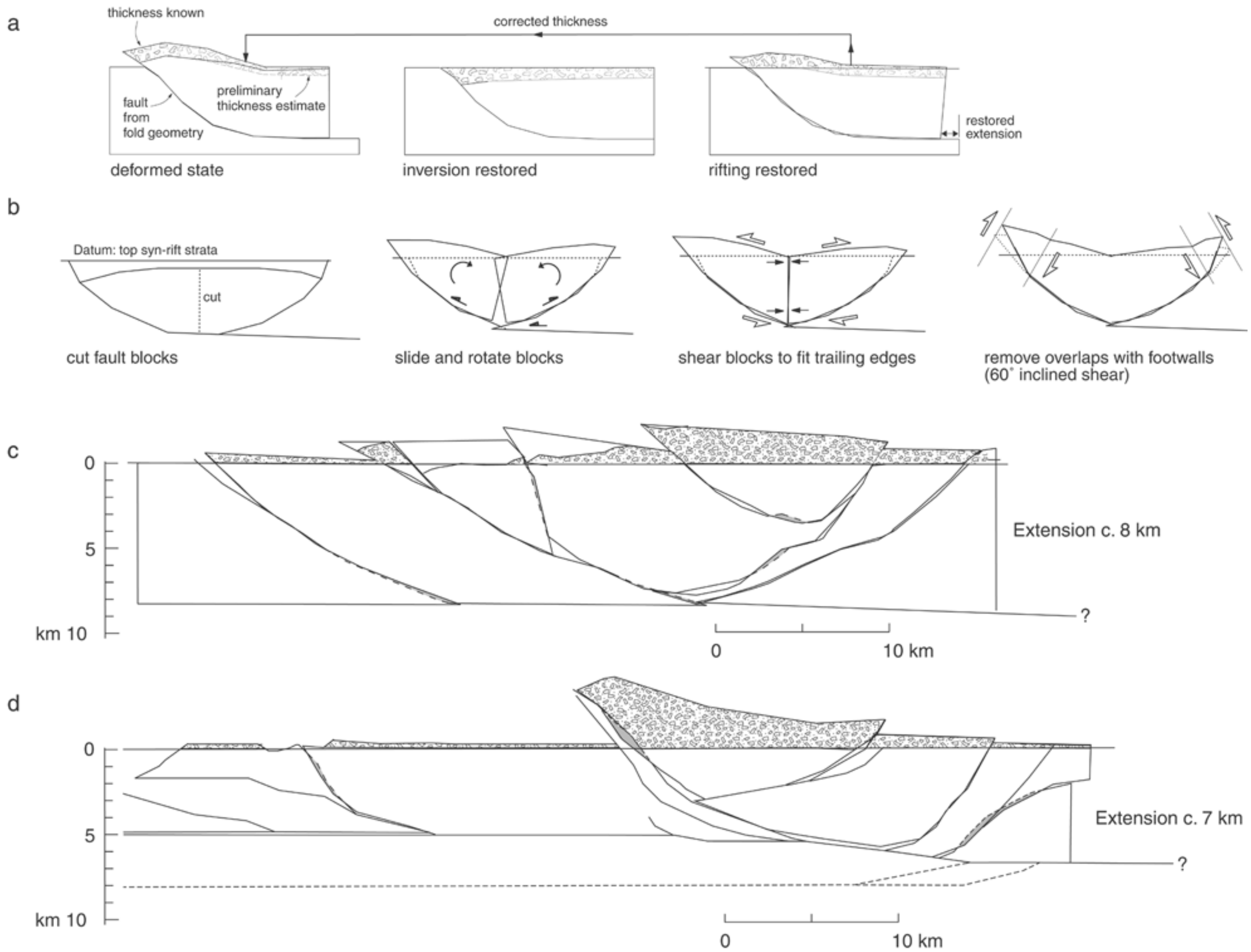


Figure 11. Restored cross sections (Figure 8b and 9b) further restored to pre-rift situation. (a) Locally known thickness of syn-rift strata constrains normal fault displacement; displacement and fault geometry are used to model syn-rift stratal geometry where not exposed. (b) Details of the block restoration technique used. (c and d) Pre-rift configuration north and south of the Garrapatas transverse zone. Gaps and overlaps are shown open and shaded, respectively.

Kress, 1995]. It seems clear that the southward truncation of the detachment levels in Silurian and Devonian strata has dictated the termination of thin-skinned thrusting [*Belotti et al.*, 1995]. The gap in foreland deformation apparently formed because major thrust reactivation of Cretaceous normal faults only set in where these change trend from ENE to NNE, more perpendicular to the Neogene contraction direction [*Kley et al.*, 1999]. The lack of foreland structures between the Subandean Ranges and the Santa Barbara System requires that shortening be transferred from the foreland to the Eastern Cordillera at the southern end of the Subandean Ranges and back to the foreland at the northern end of the Santa Barbara System. Since no discrete strike slip faults are evident there, the displacement is probably transferred by sinistral shear over a wider area. Apparently related to this diffuse transfer zone are the anomalous SSE trend and the plunge of the Zapla anticline. The anticline splays from the front of the Eastern Cordillera near 23°45′S at an angle of almost 45° in map view (Figure 3). From about 24°S it plunges consistently to the SSE until its termination at the latitude of the GTZ. The SSE trend appears to reflect finite strain axes rotated due to E-W sinistral shear while the decreasing fold amplitude suggests an increasing amount of shortening accommodated in the Santa Barbara System.

[29] The southern boundary of the Santa Barbara System with the Sierras Pampeanas is marked by an abrupt increase in the wavelength of structures near 26°S [*González and Mon*, 1996]. This structural break essentially coincides with the southern termination of the Cretaceous rift (Figures 1 and 12), although the shallow southernmost branch of the rift overlaps the Cumbres Calchaquies basement uplift west of Tucumán, and inversion of another Cretaceous basin was documented farther south in one of the Sierras Pampeanas [*Schmidt et al.*, 1995]. Nevertheless, most of the Sierras Pampeanas basement thrusts do not appear to be reactivated normal faults. *Mon* [1972] argued that the Santa Barbara System/Sierras Pampeanas boundary reflects the transition

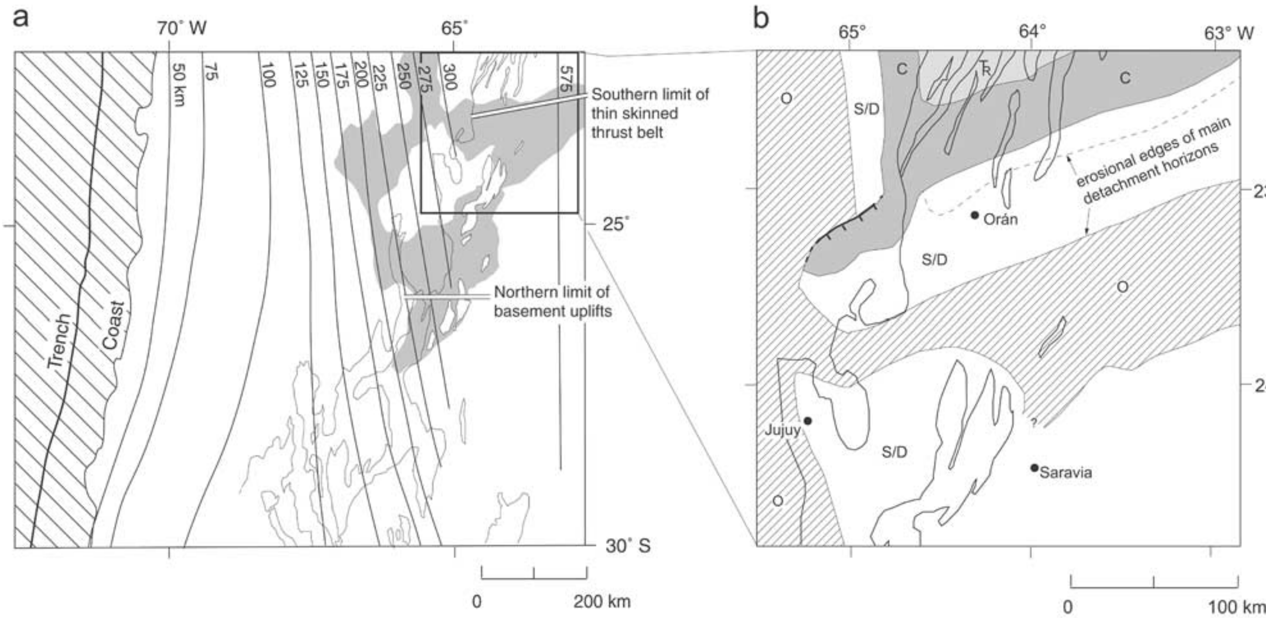


Figure 12. The northern and southern boundaries of the Santa Barbara System (a) compared to the geometry of the subducting Nazca plate shown by depth contour lines [*Cahill and Isacks*, 1992] and the extent of the Cretaceous rift (shaded), (b) compared to a Cretaceous/Tertiary subcrop map (modified from *di Persia et al.* [1991]). The termination of thin-skinned deformation is due to erosion of shaly detachment horizons in Silurian/Devonian strata, while the onset of deep-seated basement thrusting coincides with the southern boundary of deep rift basins. Plate geometry changes little along the width of the Santa Barbara System.

from low to higher metamorphic grade in the Precambrian to Early Cambrian basement. This is not necessarily in conflict with the observation that the rift structures have been important, because mechanical properties of the basement may already have controlled the extent and orientation of the rift basins.

4.4. Crustal-Scale Geometry of Neogene Contraction Structures

[30] In order to produce consistent structural cross-sections we had to extrapolate surface structures to considerable depth. Independent evidence for the deep structural geometries comes from a detailed seismologic survey of the Santa Barbara foreland and Zapla areas [*Cahill et al.*, 1992]. Our extrapolated fault traces coincide quite well with the hypocenter distribution beneath the seismically very active Zapla range (Figure 13). Farther east, the basal detachment we propose for the Santa Barbara System lies within the depth range of the scarcer, more scattered events there. However, the single major event with a focal mechanism solution is considerably deeper.

[31] Although the flexural rigidity of the foreland lithosphere has been calculated to be low at the latitude of the Santa Barbara System (see above), there are still marked deviations from perfect local isostasy for wavelengths of several tens of kilometers. In Figure 14 the Moho geometry as determined by *Whitman* [1994] is compared to the Moho as predicted from local Airy compensation of the topography with crust and mantle densities of 2.73 and 3.2 g cm^{-3}. While there is no local compensation for the mountains of the Santa Barbara System, the Moho farther west is too deep up to the front of the Eastern Cordillera, suggesting that the load of the Eastern Cordillera is in part regionally compensated. The Moho geometry in the foreland is consistent with thrusting on the major west dipping fault which we assume to link the foreland structures to the Eastern Cordillera (Figure 14). However, in contrast with the situation farther north, the reduced amount of foreland thrusting contributes little to crustal thickening and surface uplift in the high Andes.

5. Discussion

[32] The timing of earliest contraction in the Santa Barbara System is a matter of debate. Mild inversion was inferred to have occurred well before the main Pliocene deformation, because the Middle Miocene base of the foreland basin succession truncates the Santa Barbara subgroup in an area termed the Los Gallos high [*Salfity et al.*, 1993], locally down to its base. This view was challenged by *Cristallini et al.* [1997], who interpreted that thinning of the Santa Barbara subgroup on the Los Gallos high reflects non-deposition over a flat part of an extensional master detachment. They also pointed out that the thickness maxima of the syn-rift and post-rift successions do not coincide (compare Figures 8b and 9b) and attributed this to the

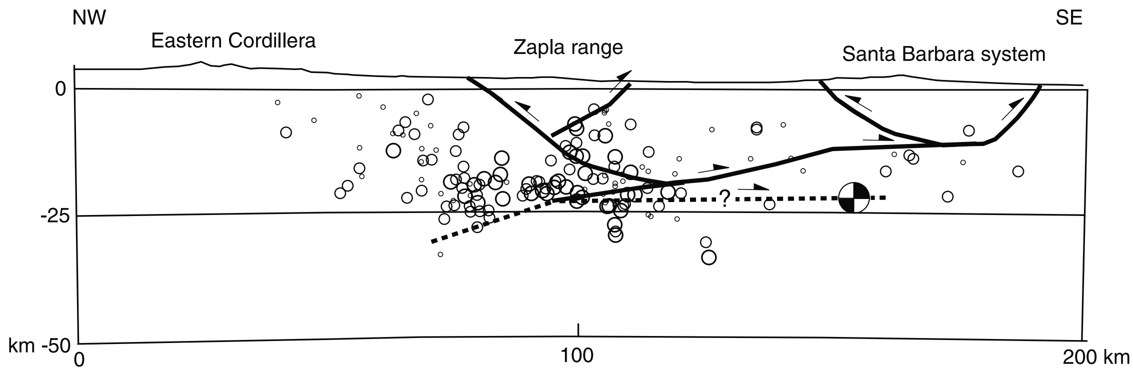


Figure 13. Modern seismicity of the Zapla range and Santa Barbara System (after *Cahill et al.* [1992]) compared to the main fault geometries inferred from surface structures. Agreement is good for the Zapla range, but the only event with a focal mechanism solution is markedly deeper than the basal detachment in the Santa Barbara System. This may indicate a deeper detachment (dashed) now propagating toward the foreland.

hanging wall moving over ramps and flats. Alternatively, the shifting patterns of subsidence and local uplift could reflect ductile hot lower crust flowing from beneath elevated graben shoulders [*McKenzie et al.*, 2000].

[33] The detachment we derive from structural extrapolation is markedly shallower than the one at about 20 km depth proposed by *Cahill et al.* [1992] essentially based on the single well-determined hypocenter and focal mechanism solution available. Since *Cahill et al.*'s [1992] basal detachment is too deep to be compatible with the relatively short wavelength folds in the Santa Barbara System, their cross section also includes a shallower detachment in Paleozoic sedimentary rocks which links up with the deep detachment over a west dipping ramp. Apart from the thin-skinned interpretation of the Santa Barbara System which results from an exaggerated thickness of Paleozoic strata, this structural geometry is similar to the one we propose here. However, the west dipping ramp in Cahill et al.'s model is far to steep to fit the gently dipping east limb of the Lavayén syncline. It is therefore possible that part of the modern seismicity beneath the Santa Barbara System has no direct relation to the structures at the surface. Deep earthquakes may occur on a new subhorizontal detachment that is now propagating eastward from beneath the Eastern Cordillera. Continued displacement on such a deep detachment would produce broad basement structures similar to the Sierras Pampeanas, suggesting that the Pampeanas type of foreland basement thrusting may presently be expanding northward along the strike of the Andes. The alternative assumption that the Santa Barbara System is not linked to the Eastern Cordillera by a deep detachment at all (discussed by *Cahill et al.* [1992] and *Allmendinger and Zapata* [2000]) is compatible with the seismologic data. However, the west dipping Moho in the foreland east of the Andes is difficult to explain in such a model, just as the lack of a local Moho keel caused by crustal shortening beneath the Santa Barbara system.

[34] Both the northern and southern boundaries of the Santa Barbara System are sharp and coincide with major stratigraphic discontinuities. By contrast, the dip of the underlying subducting Nazca plate varies smoothly from moderately steep in the north to subhorizontal in the south [*Cahill and Isacks*, 1992]. This suggests that a direct control of slab dip on the present foreland structural segmentation is unlikely. However, the deep crustal seismicity beneath the Santa Barbara System may indicate that foreland structural styles and segment boundaries are shifting with time.

[35] The amount of shortening accommodated in the foreland decreases considerably from the Subandean Ranges to the Santa Barbara System, from about 70–100 km to just 25–30 km. This implies that foreland contraction in the Santa Barbara System and farther south hardly contributes to the uplift of the Andes, and that thrusting and folding in the Eastern Cordillera and the Puna plateau must increase to thicken the crust there [*Allmendinger and Gubbels*, 1996; *Kley*, 1996]. This is in keeping with the strong seismic activity at the front of the Eastern Cordillera [*Cahill et al.*, 1992] (see Figure 13). However, the only moderately thickened crust of the southern Puna [*Yuan et al.*, 2000] indicates that the decrease in foreland contraction is only partly compensated by shortening within the mountain belt. Uplift due to thinning of the mantle lithosphere is likely to be important in the regions where foreland shortening is weak [*Whitman et al.*, 1996].

6. Conclusions

[36] The Santa Barbara segment of the Andean foreland thrust belt exhibits a basement-involved structural style essentially controlled by the Neogene deformation front impinging on the Cretaceous Salta group rift and the resulting inversion of normal faults between 23°30 and 27°S. However, some faults along the western margin of the Santa Barbara System and those of the Zapla anticline to the west appear to be newly formed thrusts. A deep-seated, gently west dipping thrust which we infer to connect the Eastern Cordillera and Zapla Range with the Santa Barbara System probably nucleated as a link between a deep detachment beneath the Eastern Cordillera and the shallower zone of mechanical weakness provided by the Salta rift. This

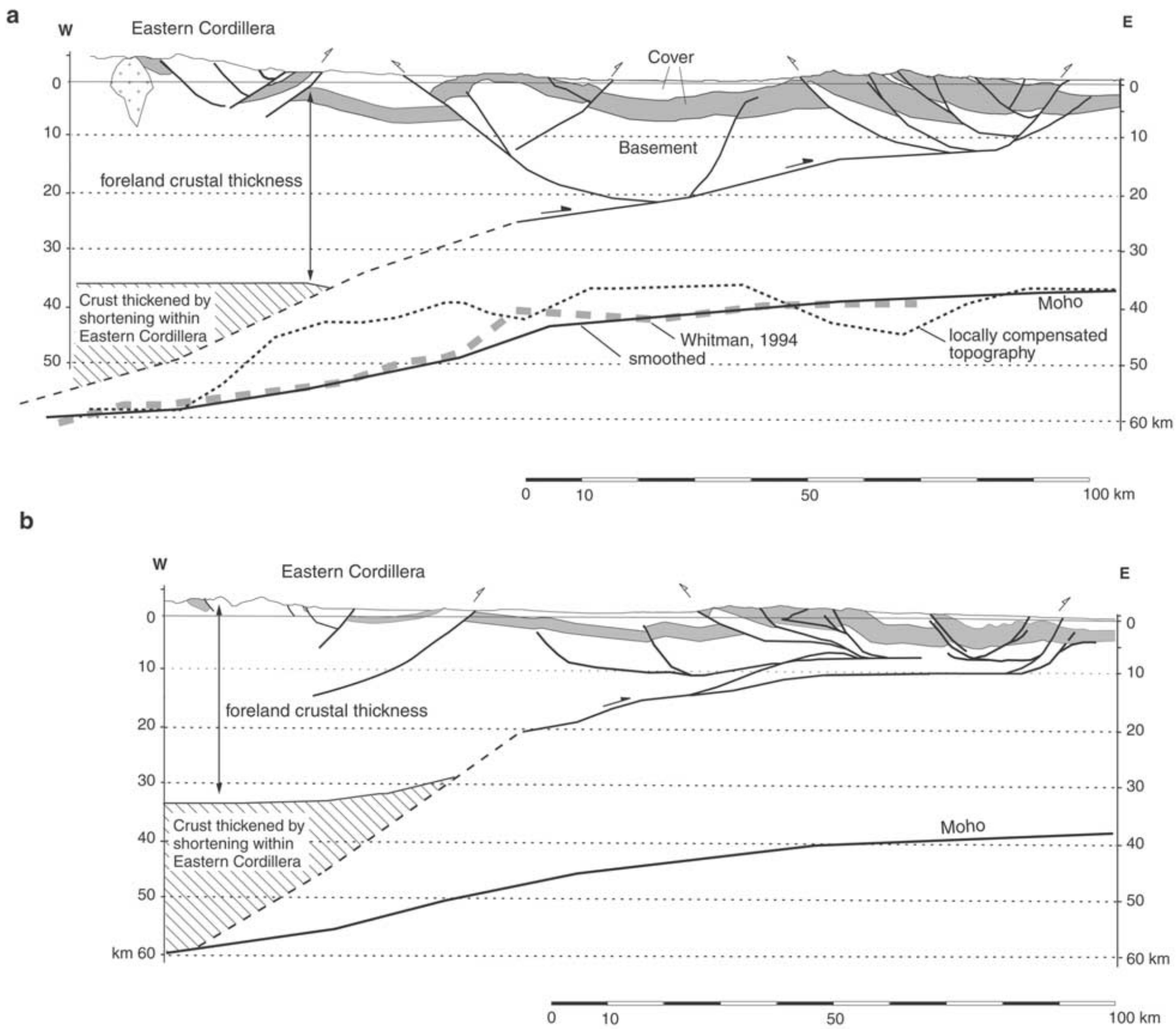


Figure 14. Crustal-scale cross sections along the lines of (a) Figure 8 and (b) Figure 9, extended westward. Moho geometry after *Whitman* [1994] (thick gray, dashed) and slightly smoothed (continuous). Also shown is hypothetical Moho geometry predicted from locally compensated topography with crust and mantle densities of 2.73 and 3.2 g cm^{-3} (solid, dashed). Deep crustal base in central part of section suggests flexural compensation of Eastern Cordillera. Foreland shortening is sufficient to explain the strong westward dip of the Moho up to the front of the Eastern Cordillera but contributes little to uplift of the high Andes. The main thrusts are continued to the base of the crust only to illustrate the amount of crustal thickening not accomplished by underthrusting foreland crust; they may in fact not extend beyond the base of the brittle upper crust.

basal thrust is not a reactivated master fault of the rift system, because no syn-rift strata accumulated on its hanging wall. Nonetheless, the subhorizontal basal décollement of the Santa Barbara System could correspond to the original master detachment of the extensional system. Extension in the Santa Barbara branch of the Salta rift system, though not very well constrained, was apparently less than 10 km.

[37] Total foreland shortening of the order of 25–30 km at 24°S is markedly less than in the thin-skinned Subandean Belt to the north (ca. 70–100 km shortening at 21–22°S) and contributes little to crustal thickening and uplift in the interior of the Andean mountain belt. The thin mantle lithosphere and low flexural rigidity of the Santa Barbara System foreland segment may in part be inherited from a thermal anomaly established during mantle-activated Cretaceous rifting.

[38] The along-strike changes from thick-skinned deformation in the Santa Barbara System to thin-skinned thrusting in the Subandean Ranges and deep-seated basement thrusting in the Sierras Pampeanas are sharp and coincide with pronounced Cretaceous or older stratigraphic hetero-

geneities, arguing against a direct control of the smoothly changing Nazca slab dip on foreland structural style.

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