TECTONICS, VOL. 11, NO. 3, PAGES 523-536, JUNE 1992

GEOMETRY AND KINEMATIC EVOLUTION OF PASSIVE ROOF DUPLEXES DEDUCED FROM CROSS SECTION BALANCING: EXAMPLE FROM THE FORELAND THRUST SYSTEM OF THE SOUTHERN BOLIVIAN SUBANDEAN ZONE

Patrice Baby,[1] Gérard Hérail,[2] René Salinas,[3] and Thierry Sempere[4]

Abstract. The Subandean Zone of Bolivia is a foreland fold and thrust belt which forms the eastern edge of the central Andes mountains. Between 19°S and 22°S latitude, the construction of five balanced cross sections shows that the N-S trending Subandean Zone is characterized by the existence of passive roof duplexes. These complex structures can be distinguished by the lithotectonic unit within which duplexing occurs. The five balanced cross sections permit the geometric and kinematic analyses of these passive roof duplexes. The sequential restorations of certain cross sections reveal a possible development of a piggy back sequence of three passive roof duplexes. Apparently, these passive roof duplexes propagated toward the foreland from deeper and deeper lithotectonic units. While a passive roof duplex was developing, the sole thrust stuck and the major horizontal displacements were then transferred either to out-of-sequence thrusts or to a new sole thrust, in a deeper detachment horizon. Therefore each passive roof duplex would correspond to the orogenic front of the Andean range at one very particular time in the history of the Subandean Zone of southern Bolivia. From south to north, the quantitative analysis by cross section balancing shows a transfer of displacement from the hinterland structures to the passive roof duplex that forms the present orogenic front. Available data do not permit us to explain completely this phenomenom.

[1]Institut Français de Recherche Scientifique pour le Développement en Coopération, Santa Cruz, Bolivia.

[2]Institut Français de Recherche Scientifique pour le Développement en Coopération, La Paz, Bolivia.

[3]Yacimientos Petroliferos Fiscales Bolivianos, Gerencia de Exploracion, Santa Cruz, Bolivia.

[4]Institut Français de Recherche Scientifique pour le Développement en Coopération, Paris, France.

Paper number 91TC03090.
0278-7407/ 92 / 91TC-03090$10.00

INTRODUCTION

The classification and importance of blind thrusts in foreland thrust systems have recently been established worldwide [Charlesworth and Gagnon, 1985; Morley, 1986; Vann et al., 1986; Jones, 1987; Dunne and Ferril, 1988].

One of the most spectacular types of blind thrust systems is the passive roof duplex which characterizes many frontal regions of mountain belts. Banks and Warburton [1986, p. 229] defined a passive roof duplex as a duplex "whose roof thrust has backthrust sense (passive roof thrust) and whose roof sequence remains relatively 'stationary' during foreland directed piggy-back style propagation of horse within the duplex". The roof sequence is generally pinned to the thrust system immediately beyond the active horse tip line. Known examples of this kind of structure are found in the Alps [Fallot, 1949], in the Rocky Mountain foothills [Gordy et al., 1977; Price, 1981; Jones 1982], in the Sulaiman Range of Pakistan [Banks and Warburton, 1986], in Taiwan [Suppe and Namson, 1979; Suppe, 1980], in the Mackenzie Mountains of Canada, Alaska and the central Andes of Peru [Vann et al., 1986], in the Pyrenees [Baby, 1988; Baby et al., 1988; Déramond et al., 1990] and in the Andes of Argentina [Wines, 1990].

The purpose of this paper is to present not only another example of a mountain front characterized by passive roof duplexes but also how cross sections balancing permits geometric and kinematic analysis of these passive roof duplexes and study of their lateral variation.

This study was carried out in the Subandean Zone of southern Bolivia between 19°S and 22°S latitude (Figure 1). Construction of balanced cross sections has been made possible due to surface mapping, reflection seismic data, and drilling information provided by the Bolivian State Oil Company (YPFB).

GEOLOGIC FRAMEWORK

The Subandean Zone of Bolivia is a foreland fold and thrust belt [Oller, 1986; Sheffels, 1986, 1988; Roeder, 1988; Baby et al., 1989; Hérail et al., 1990] that forms the eastern edge of the central Andes mountains and whose deformation started in the Late Oligocene and is still developing [Martinez, 1980; Oller, 1986; Sempere et al., 1990]. In southern Bolivia, between 19°S and 22°S latitude, the N-S trend and the 100 to 140-km-wide Subandean Zone is bounded at the Cordillera Oriental edge by the Main Frontal Thrust (CFP "Cabalgamiento Frontal Principal" [Sempere et al., 1988, 1990]), whereas the orogenic front developed below the Chaco Plain at the eastern edge (Figure 1). An important east verging thrust (Mandiyuti Thrust)

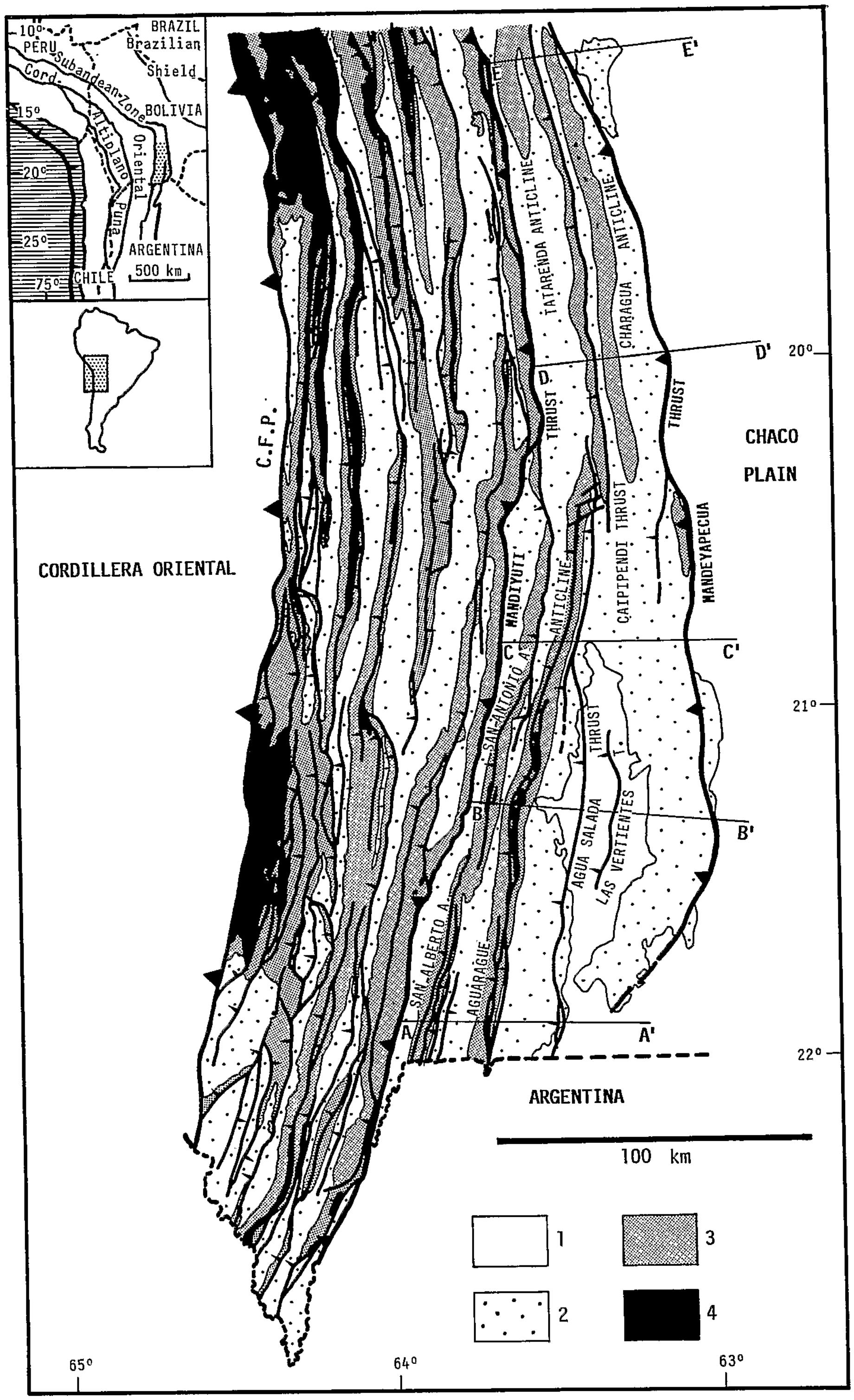

Fig. 1. Geologic map of the southern Bolivian Subandean Zone (after Pareja and Ballón [1978] and unpublished 1:20,000 scale YPFB maps), showing locations of balanced cross sections (letters A-E). Stratigraphic units are 1, Quaternary; 2, Tertiary; 3, Carboniferous to Mesozoic; and 4, Devonian. CFP is Cabalgamiento Frontal Principal (Main Frontal Thrust).

divides the southern Bolivian Subandean Zone into two fold and thrust belts that differ according to their thrust system geometry. The western belt is characterized mainly by fault propagation folds and fault bend folds, whereas the eastern belt is characterized by fault propagation folds and passive roof duplexes [Baby et al., 1989]. This study focuses on the eastern belt of the southern Bolivian Subandean Zone.

The material involved in Subandean thrusting in Bolivia consists of a practically continuous series from Silurian to Jurassic and a Late Oligocene to recent foredeep fill [Pádula, 1959; López, 1974]. The stratigraphic column in the study area is subdivided into a number of lithotectonic units (Figure 2) which play important roles in controlling the structural geometry. The main detachments are located in the Silurian dark shales (Kirusillas detachment), in the early Devonian shales (Icla detachment), and in the base and top of the Middle to Late Devonian dark shales of the Los Monos Formation. The Silurian-Devonian succession is covered by more than 2000 m of late Paleozoic and Mesozoic sandstones with no potential detachments; in some places it is also covered by several thousand meters of synorogenic Tertiary sedimentary rocks.

BALANCED CROSS SECTIONS

In order to study the lateral variation in structural geometry within the eastern Subandean Zone of southern Bolivia, surface data, regional cross sections, and well and seismic reflection data were integrated to construct five balanced cross sections between the Mandiyuti Thrust and the Chaco plain. These east striking balanced cross sections are located where the lateral variations of structures are significant (Figures 1 and 3). The five balanced cross sections are shown in Figures 4, 5, 6, 7, and 8.

Surface data were obtained from 1:20,000 YPFB geologic maps and regional cross sections and also from field reconnaissance of the area. Unpublished seismic reflection and well data (locations in Figure 3) provided by YPFB were used to interpret the depth structures.

The cross sections were constructed and balanced on the basis of the consistency of bed lengths and restorability of the cross sections [Dahlstrom, 1969; Woodward et al., 1985]. Since no penetrative strain is observed in the outcrops of the southern Bolivian Subandean Zone and the CFP hanging wall, penetrative strain is assumed to be either nonexistent or insignificant in the deep thrust structures (e.g., in duplex construction). At least portions of hanging wall cutoffs are preserved on all emergent imbricates; therefore all emergent thrust displacements can be measured. The variations in thicknesses are insignificant and do not hamper the cross section balancing. Strike-slip motions have not been observed, and the orientation of the cross sections is parallel to the direction of tectonic transport.

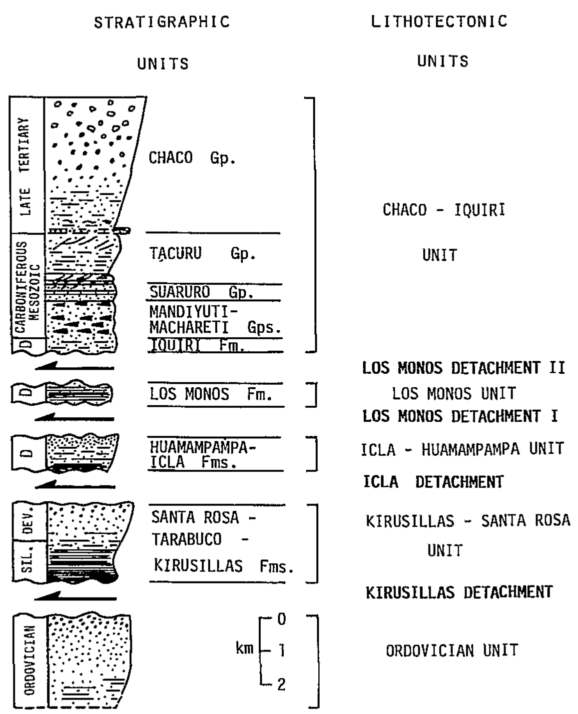

Fig. 2. Stratigraphic and lithotectonic units in the southern Bolivian Subandean Zone.

Construction of the Depth Sections

The stratigraphic thicknesses above the Icla-Huamampampa lithotectonic unit are determined from wells. In various seismic reflection lines, the Los Monos and the Chaco-Iquiri lithotectonic units have been identified by drilling. These data show the disappearance of the Iquiri Formation toward the southwest (cross sections AA' and BB', Figures 4 and 5). In all the seismic reflection lines, the Icla-Huamampampa lithotectonic unit has been identified by a typical seismic marker calibrated by wells east of the study area. This good marker has permitted the definition of several structural geometries in the eastern half of the depth sections. Below this good seismic marker, the thickness of the Kirusillas-Santa Rosa lithotectonic unit is largely hypothetical because in general data obtained from seismic reflection techniques do not reach its base. Only in the eastern half of the cross section AA' (Figure 4), seismic reflection lines show the Kirusillas detachment. These seismic reflection data show also a westward increase in the thickness of the Kirusillas-Santa Rosa lithotectonic unit. In the rest of the study area, it is assumed that the Kirusillas-Santa Rosa lithotectonic unit has the same thickness as near the Cordillera Oriental boundary in the CFP hanging wall.

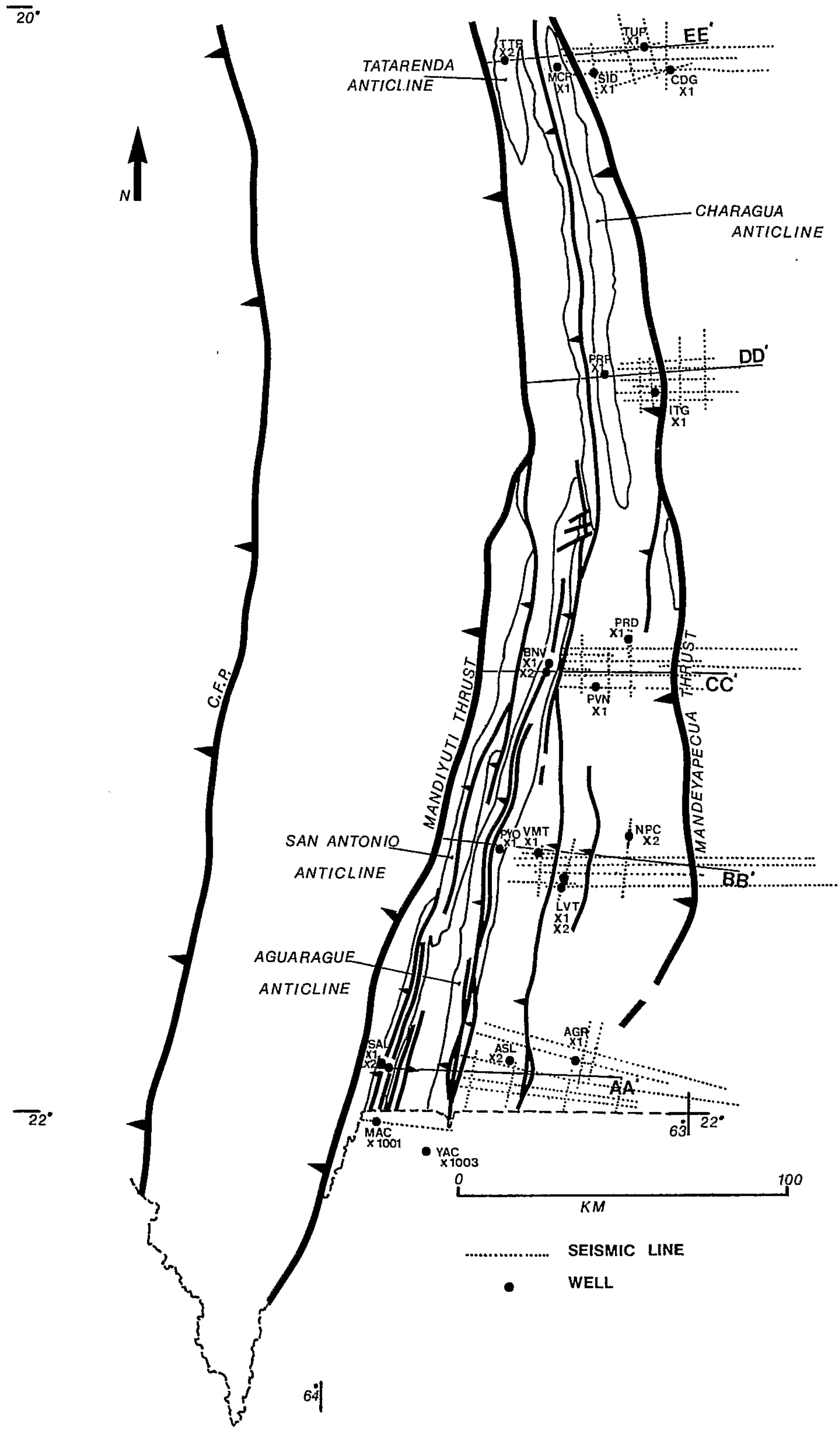

Fig. 3. Map of the principal structures of the eastern belt of the southern Bolivian Subandean Zone with locations of wells and seismic reflections lines used in the study.

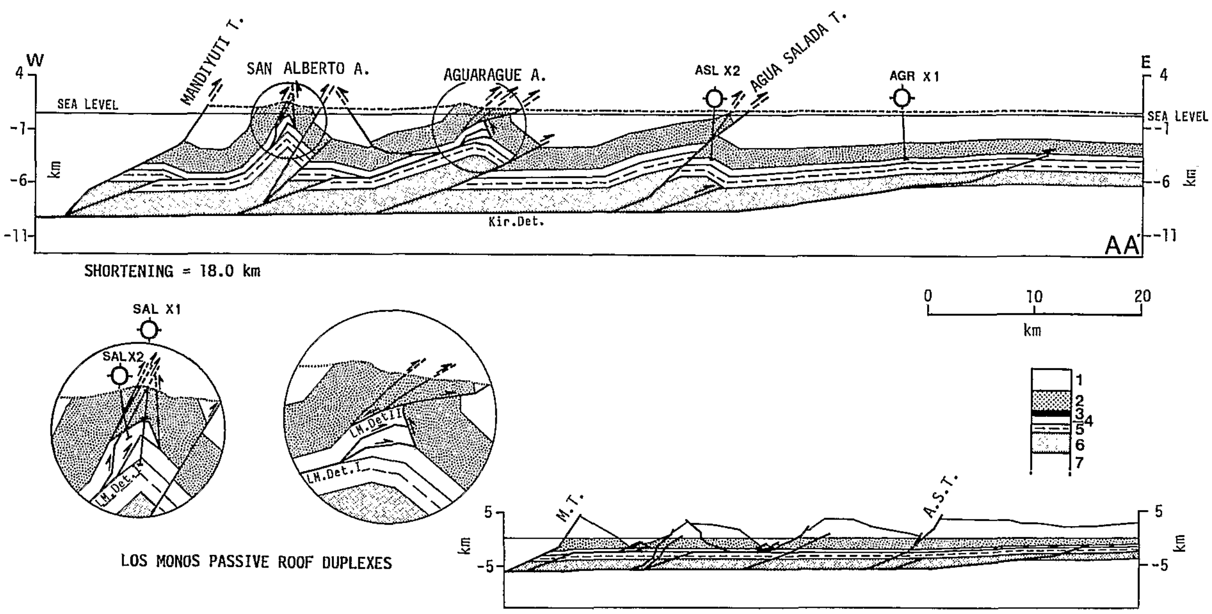

Fig. 4. Balanced cross section A-A' and restored counterpart. The scale of the restored section is 50% that of the cross section. Location is in Figure 1. Stratigraphic units are 1, Tertiary; 2. Mesozoic-Permian-Carboniferous; 3, Los Monos Formation; 4, Icla-Huamampampa formations; 5, Kirusillas-Tarabuco-Santa Rosa formations; and 6, Ordovician. Detachment are Kir. Det., Kirusillas Detachment; LM. Det. I, Los Monos Detachment I; and LM. Det. II, Los Monos Detachment II. T is thrust and A is anticline.

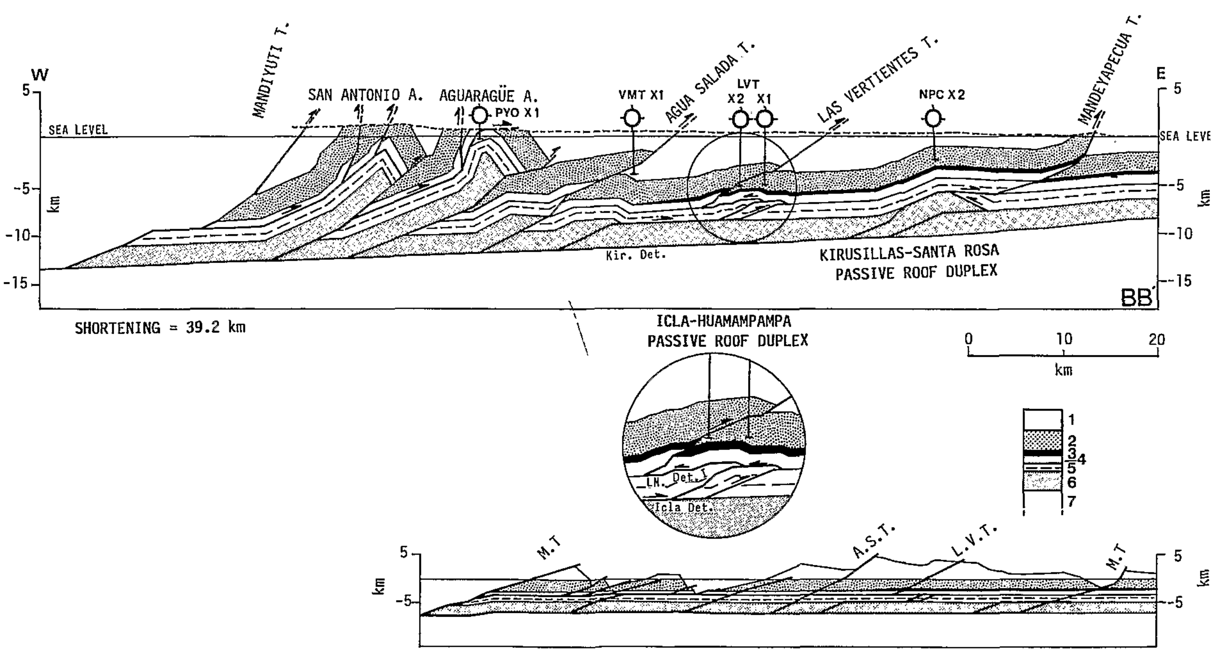

Fig. 5. Balanced cross section B-B' and restored counterpart. The scale of the restored section is 50% that of the cross section. Location is in Figure 1. Stratigraphic units are 1, Tertiary; 2, Mesozoic-Permian-Carboniferous; 3, Iquiri Formation; 4, Los Monos Formation; 5, Icla-Huamampampa formations; 6, Kirusillas-Tarabuco-Santa Rosa formations; and 7, Ordovician. Detachments are Kir. Det., Kirusillas Detachment; Icla. Det., Icla Detachment; and LM. Det. I, Los Monos Detachment I. T is thrust and A is anticline.

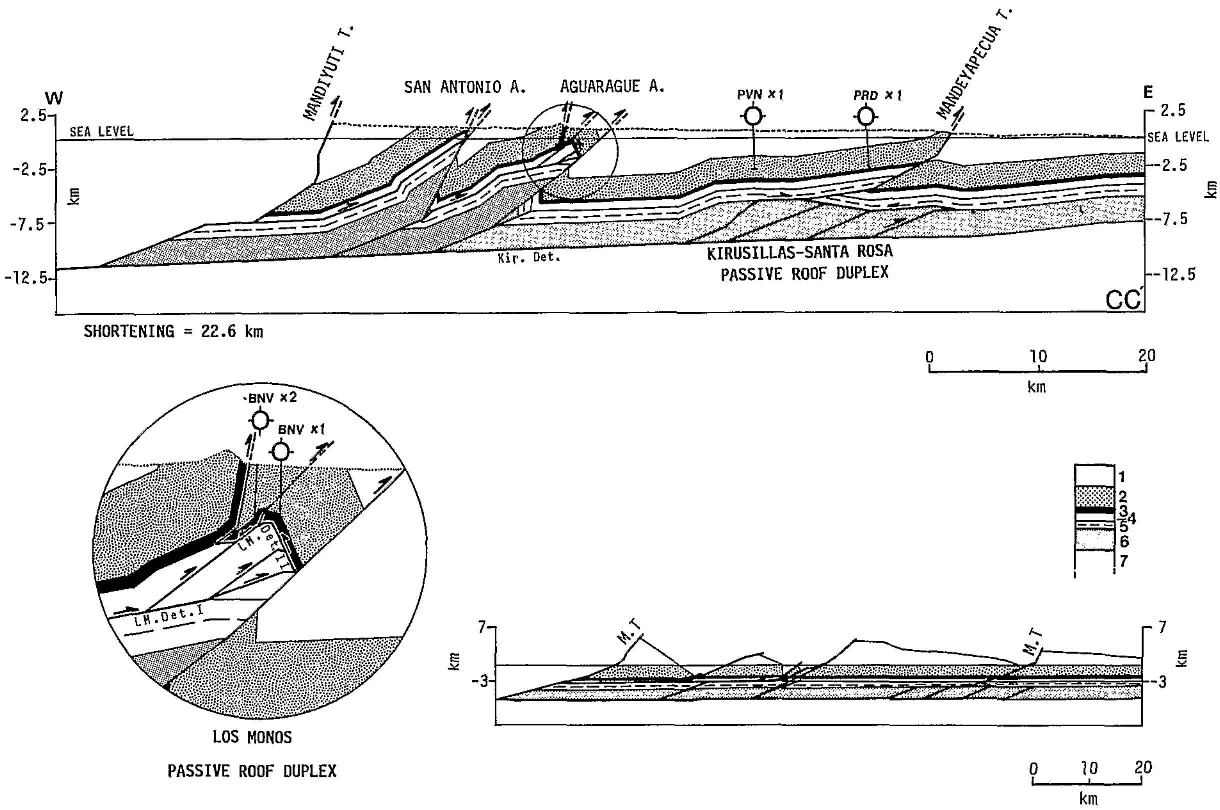

Fig. 6. Balanced cross section C-C' and restored counterpart. The scale of the restored section is 50% that of the cross section. Location is in Figure 1. Stratigraphic units are 1, Tertiary; 2, Mesozoic-Permian-Carboniferous; 3, Iquiri Formation; 4, Los Monos Formation; 5, Icla-Huamampampa formations; 6, Kirusillas-Tarabuco-Santa Rosa formations; and 7, Ordovician. Detachment are Kir. Det., Kirusillas Detachment; LM. Det. I, Los Monos Detachment I; and LM. Det. II, Los Monos Detachment II. T is thrust and A is anticline.

The Ordovician and the basement are not involved in the foreland thrust system of the Subandean Zone of southern Bolivia [Baby et al., 1989; Hérail et al., 1990]. Therefore we have used the Kirusillas detachment as the basal decollement for the construction of the five balanced cross sections.

Seismic data (locations in Figure 3) were used to construct a foredeep with a bottom that slopes mountainward at 1° to 3°. The geometry and the slope of this regional flexure vary from south to north and from west to east.

In the cross sections AA', BB', and CC' (Figures 4, 5, and 6), east of the Aguaragüe Anticline, the structural geometry of the upper part is well constrained by surface data, wells, and seismic reflection markers. However, the lower part below 7000 m is poorly constrained; it was drawn using fragmentary seismic reflectors, geometric construction (flats and ramps), regional décollement levels and thicknesses (Figure 2), and structural interpretation by cross section balancing. The geometries of the San Alberto Anticline and Aguaragüe Anticline are poorly constrained in the Subandean Zone of Bolivia (geologic mapping and wells). However, in Argentina close to the Bolivian border, the geometries of these two complex anticlines are revealed by a seismic reflection line and well data (locations in Figure 3).

In the cross sections DD' and EE' (Figures 7 and 8), the upper part of the Charagua Anticline and its foreland are well constrained by surface data and seismic reflection markers reached by drilling. The upper part of the Tatarenda Anticline is constrained only by surface data and well data. The lower part of these two anticlines, which involves the Kirusillas-Santa Rosa lithotectonic unit, was drawn using geometric construction (flats and ramps), regional geologic background (Figure 2), and structural interpretation by cross section balancing.

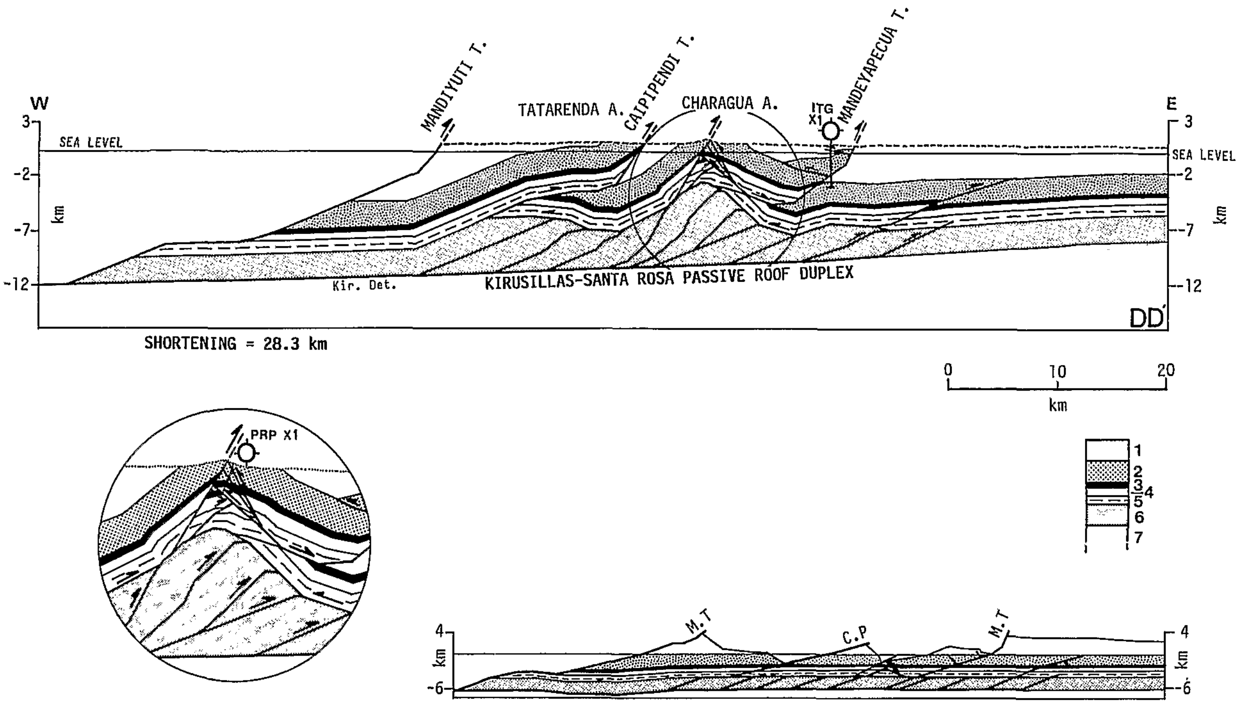

Fig. 7. Balanced cross section D-D' and restored counterpart. The scale of the restored section is 50% that of the cross section. Location is in Figure 1. Stratigraphic units are 1, Tertiary; 2, Mesozoic-Permian-Carboniferous; 3, Iquiri Formation; 4, Los Monos Formation; 5, Icla-Huamampampa formations; 6, Kirusillas-Tarabuco-Santa Rosa formations; and 7, Ordovician. Kir. Det. is Kirusillas Detachment. T is thrust and A is anticline.

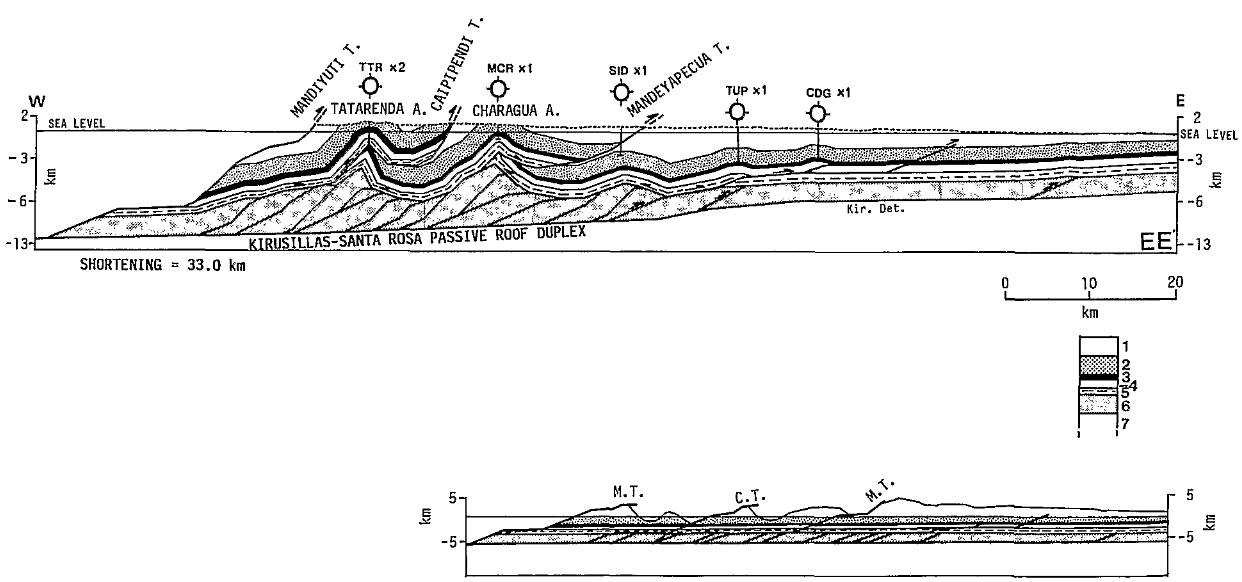

Fig. 8. Balanced cross section D-D' and restored counterpart. The scale of the restored section is 50% that of the cross section. Location is in Figure 1. Stratigraphic units are 1, Tertiary; 2, Mesozoic-Permian-Carboniferous; 3, Iquiri Formation; 4, Los Monos Formation; 5, Icla-Huamampampa formations; 6, Kirusillas-Tarabuco-Santa Rosa formations; and 7, Ordovician. Kir. Det. is Kirusillas Detachment. T is thrust and A is anticline.

Passive Roof Duplexes Geometry

The balanced cross section method allows us to interpret the main anticlines as passive roof duplexes that can be distinguished by the lithotectonic unit within which duplexing occurs.

Kirusillas-Santa Rosa passive roof duplex. In the cross sections BB', CC', DD', and EE' (Figures 5, 6, 7, and 8), the orogenic front corresponds to an emergent forethrust (Mandeyapecua Thrust) deformed by blind thrusting. From south to north, the width of this blind thrust and the offset of the Mandeyapecua Thrust increase. In the cross sections DD' and EE' (Figures 7 and 8), west to the Mandeyapecua Thrust, a second emergent forethrust (Caipipendi Thrust) also deformed by blind thrusting appears. Apparently, the offset of these two emergent forethrusts is related to the width of the blind thrusts that deformed them. To explain these relationships and the deformation of the Mandeyapecua Thrust and Caipipendi Thrust, we interpret them as passive forethrusts of a passive roof duplex that developed in the Kirusillas-Santa Rosa lithotectonic unit. The floor thrust of this passive roof duplex is located within the Silurian dark shales (Kirusillas detachment), whereas its roof thrust is located within the Early Devonian shales (Icla detachment).

The roof sequence of the Kirusillas-Santa Rosa passive roof duplex is known from seismic reflection data and/or from wells. The shortening in the foreland-propagated duplex is accommodated in the roof sequence mainly by the development of one or two forethrusts that branch from the passive roof thrust. Thus the Mandeyapecua and the Caipipendi forethrusts accommodated the shortening in the same Kirusillas-Santa Rosa duplex and developed passively (Figures 7 and 8); their footwalls are transported toward the hinterland, relative to the duplex propagation. The relatively "stationary" roof sequence is also characterized by thrusts with small offsets that may form triangle zones. In the cross section E-E' (Figure 8), other forethrusts with small offsets developed beyond the leading branch of the duplex. They reflect a little transfer of displacement from the blind thrust system toward the foreland. However, this displacement is minor in comparison with that transferred in the passive roof sequence of the duplex.

Icla-Huamampampa passive roof duplex. This passive roof duplex is revealed by seismic reflection data and wells; its floor thrust is located within the Early Devonian shales (Icla detachment), while its roof thrust is located within the base of the Devonian dark shales of the Los Monos Formation (Los Monos detachment I). It is seen only in cross section BB' (Figure 5) because of its limited N-S development along strike (Figure 9). It is related to the footwall of the Agua Salada Thrust which branches from the Kirusillas detachment. The displacement of the Agua Salada footwall, which is formed by a fault bend fold, is transferred to the Icla detachment permitting the development of the Icla-Huamampampa passive roof duplex. As in the Kirusillas-Santa Rosa passive roof duplex, the shortening in the duplex is accommodated in the roof sequence by a passive forethrust, the Las Vertientes Thrust.

Los Monos passive roof duplexes. In the Aguaragüe Anticline and in the San Alberto Anticline, several wells have penetrated one or two horses developed in the 700-m-thick dark shales of the Devonian Los Monos lithotectonic unit, which is located between two more competent units (Figure 2). South of 22°S latitude, these two anticlines continue in Argentina; they have been explored by seismic reflection and drilling (locations in Figure 3), which confirmed the presence of the Los Monos duplexes. In each anticline, the shortening in the Los Monos duplex is accommodated in the roof sequence by passive forethrusts (Figures 4 and 5) as in the passive roof duplexes described above. The Argentine seismic data show also that each Los Monos duplex is deformed and transported by a deeper fault propagation fold. The thickness of these deep thrust sheets suggests that they have developed from the basal décollement (i.e., the Kirusillas detachment). Thus the San Alberto Anticline and the Aguaragüe Anticline have been interpreted as interferences of Los Monos passive roof duplexes with fault propagation folds (Figures 4 and 5).

The Los Monos passive roof duplexes have a modest width (one or two horses) but a considerable N-S extension (Figure 9). Although it is partly eroded, the Los Monos passive roof duplex of the Aguaragüe Anticline is known over 200 km along strike in the study area. It continues in Argentina parallel to the Los Monos passive roof duplex of the San Alberto Anticline.

DEFORMATION SEQUENCE OF PASSIVE ROOF DUPLEXES

In the southern Subandean fold and thrust belt of Bolivia, the timing of development of any particular passive roof duplex is not known. However, a study of relative chronology of the passive roof duplexes can be made. Schematic deformation sequences are proposed for the structural geometries of cross sections AA', BB', and CC' (Figures 4, 5, and 6). In the cross sections DD' and EE' (Figures 7 and 8), only one passive roof duplex has formed. It has developed in the Kirusillas-Santa Rosa lithotectonic unit and is at the origin of the structuring of the entire section. Deformation sequences are not proposed for these two cross sections because the order of development of horses in the Kirusillas Santa Rosa passive roof duplex cannot be known.

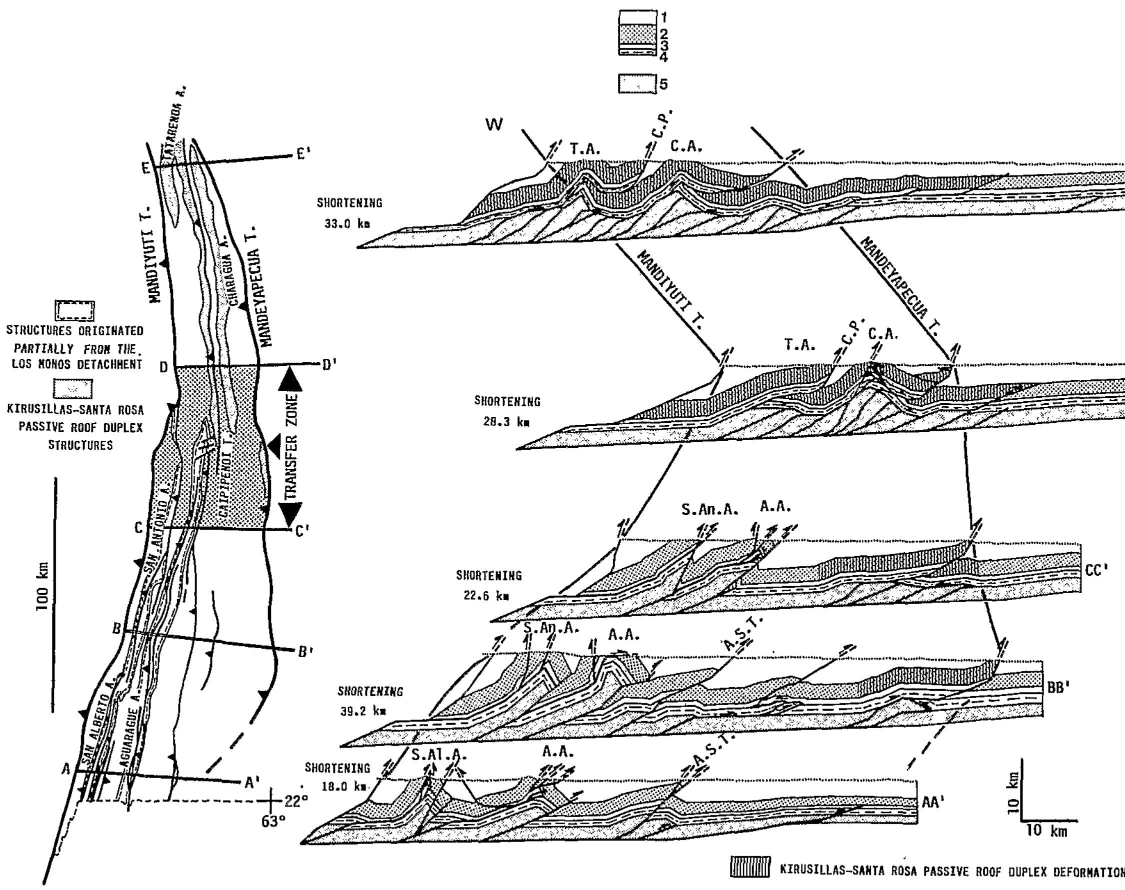

Fig. 9. Serial balanced cross sections through the eastern foreland thrust system of the southern Bolivian Subandean Zone, showing the lateral variation in structural geometry of the thrust structures. The schematic map shows a transfer zone of displacement from the hinterland structures to the Kirusillas-Santa Rosa passive roof duplex (see text) and the cross section locations. Stratigraphic units are 1, Tertiary; 2, Mesozoic-Permian-Carboniferous; 3, Iquiri-Los Monos formations; 4, Icla-Huamampampa formations; and 5, Kirusillas-Tarabuco-Santa Rosa formations. Structures are T.A., Tatarenda Anticline; C.A., Charagua Anticline; C.P., Caipipendi Thrust; S.Al.A., San Alberto Anticline; S.An.A., San Antonio Anticline; A.A., Aguaragüe Anticline; and A.S.T., Agua Salada Thrust.

Cross Section AA'

As shown above, the Alberto Anticline and the Aguaragüe Anticline correspond to Los Monos passive roof duplexes, transported and deformed by deeper fault propagation folds which branch from the basal décollement (Kirusillas detachment). Thus, apparently, the western half of the cross section AA' (Figure 4) is characterized by the development of a piggy back sequence of thrusts, which is in line with the restoration of the cross section.

In the sequential restoration (Figure 10), a first passive roof duplex forms in the Los Monos Formation and is then deformed and transported toward the foreland by the San Alberto fault propagation fold. Below this structure, a fault bend fold which branchs also from the Kirusillas detachment forms and is transported on the Los Monos detachment. The sole thrust ramps from the Kirusillas detachment to the Los Monos detachment and sticks with the development of a second Los Monos passive roof duplex. The development of the fault bend fold and the development of the second passive roof duplex are synchronous. Then, the second Los Monos passive roof duplex is transported and deformed by the Aguaragüe fault propagation fold. East of the Aguaragüe Anticline, the sequence of thrusting is hypothetical; the Agua Salada structure may have developed before or after the Los Monos passive roof duplexes.

In our sequential restoration of the cross section AA' (Figure 10), a piggy back sequence of thrusts is

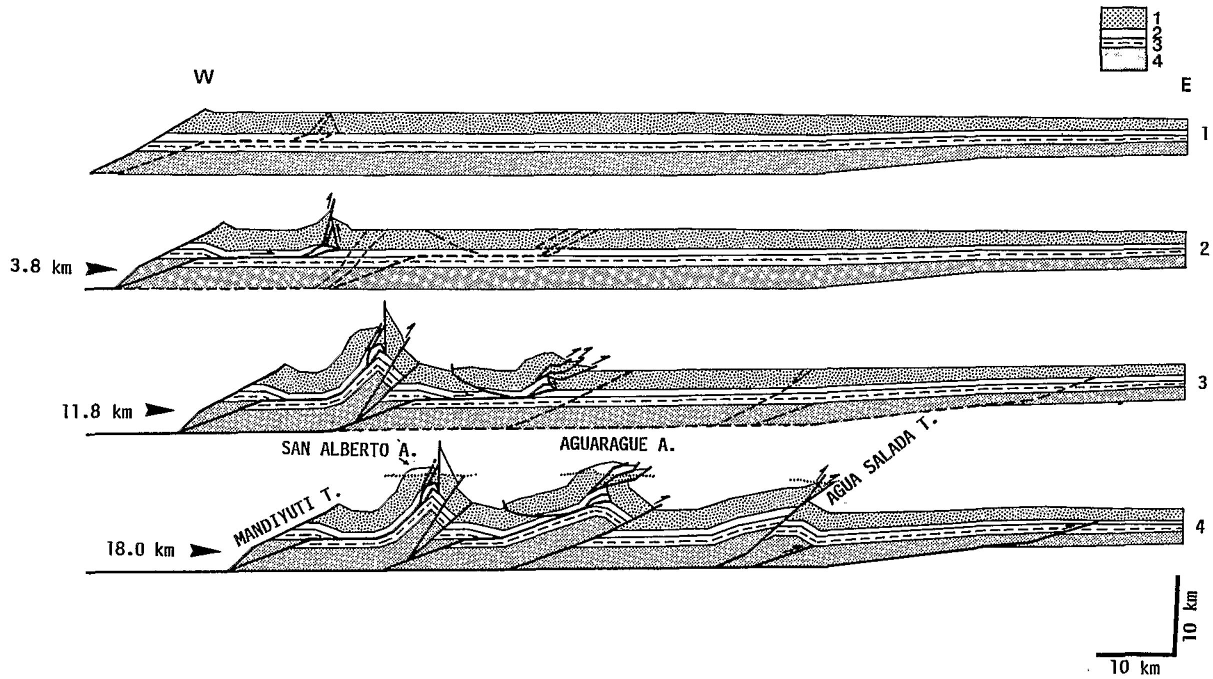

Fig. 10. Schematic deformation sequence proposed for the structural geometry of cross section A-A'. Stratigraphic units are 1, Mesozoic-Permian-Carboniferous; 2, Los Monos Formation; 3, Icla-Huamampampa formations; and 4; Kirusillas-Tarabuco-Santa Rosa formations. T is thrust and A is anticline.

drawn in the entire section. After the Aguaragüe anticline development, the propagation of deformation continues deeper on the basal décollement. The motion on the Kirusillas detachment finally dies out principally with the development of the Agua Salada structure, just west of the slope variation of the Kirusillas detachment revealed by seismic reflection data.

Cross Section BB'

The sequence of deformation (Figure 11) is slightly different. There is only one Los Monos passive roof duplex. The décollement at the base of the Los Monos Formation is deformed and cut by the San Antonio fault propagation fold, and the Los Monos passive roof duplex is transported and deformed by the Aguaragüe and the Agua Salada fault propagation folds. The Agua Salada thrust is deformed by a fault bend fold which is transported on the Icla detachment. The sole thrust ramps from the Kirusillas detachment to the Icla detachment and sticks with the development of an Icla-Huamampampa passive roof duplex. East of the Icla-Huamampampa passive roof duplex, available data do not indicate if the Kirusillas-Santa Rosa passive roof duplex developed before or after the other passive roof duplexes. As in the cross section AA', we consider in the sequential restoration (Figure 11) that the frontal structure formed ultimately. Thus the propagation of deformation dies out with the development of the Mandeyapecua structure, that is , the Kirusillas-Santa Rosa passive roof duplex.

Cross Section CC'

The sequential restoration (Figure 12) is similar to the sequential restoration of cross section BB' (Figure 11), albeit lacking the development of the Icla-Huamampampa passive roof duplex and the Agua Salada structure. The Kirusillas-Santa Rosa passive roof duplex is larger but has the same structural geometry.

LATERAL VARIATION OF THE KIRUSILLAS-SANTA ROSA PASSIVE ROOF DUPLEX

The Kirusillas-Santa Rosa passive roof duplex is present in most of the study area. Changes in geometry are summarized in Figure 9. From south to north, the Kirusillas-Santa Rosa passive roof duplex increases in size and becomes more complex. Its width increases from 15 km (cross section BB') to 50 km (cross section EE'), and its horses increase from 1 to 13. In the cross sections DD' and EE', it consists of two principal stacks of horses which are at the origin of the Charagua Anticline and Tatarenda Anticline.

A quantitative study of these changes is made

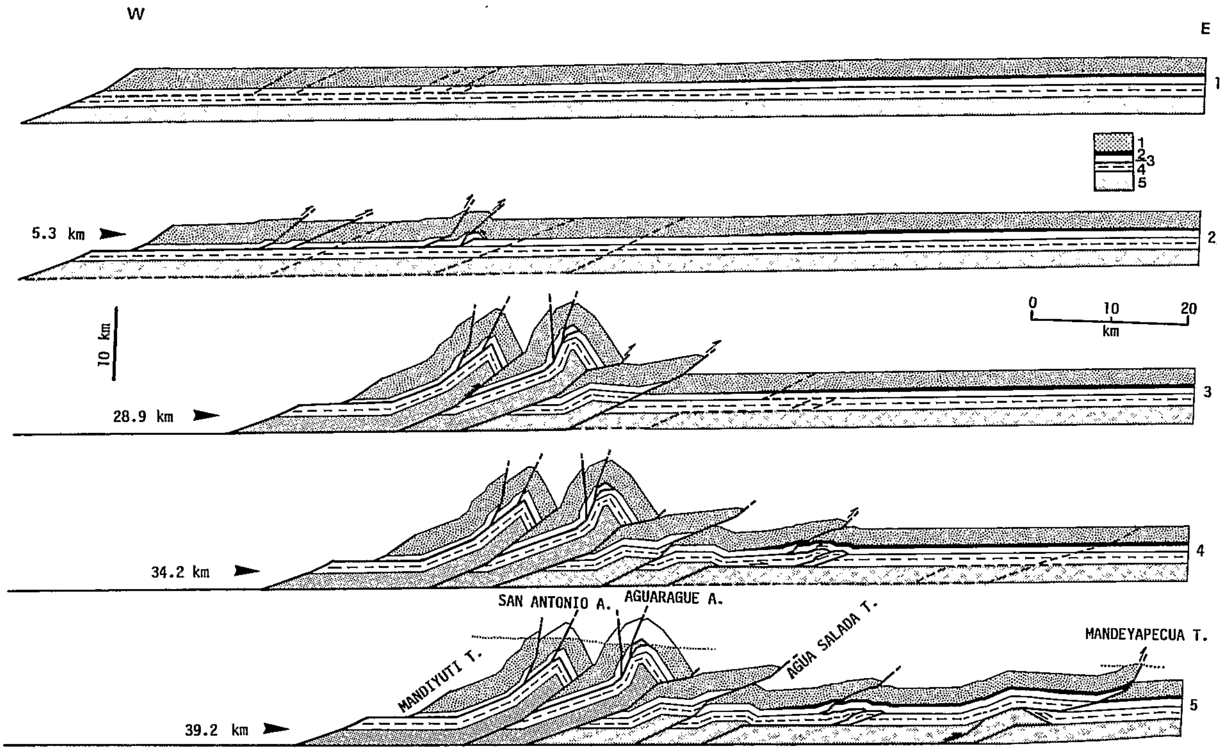

Fig. 11. Schematic deformation sequence proposed for the structural geometry of cross section B-B'. Stratigraphic units are 1, Mesozoic-Permian-Carboniferous; 2, Iquiri Formation; 3, Los Monos Formation; 4, Icla-Huamampampa formations; and 5, Kirusillas-Tarabuco-Santa Rosa formations. T is thrust and A is anticline.

from the serial balanced cross sections. Three separate calculations of shortening have been made for each balanced cross section: total shortening in the cross section, shortening in the Kirusillas-Santa Rosa passive roof duplex, and shortening in the set of the "other structures." The lateral variation of these three calculations of shortening is summarized by the three curves in Figure 13. From south to north, four stages of lateral variations are observed.

In the stage 1, between the cross sections AA' and BB', the amounts of shortening increase, reflecting the developments of the Kirusillas-Santa Rosa passive roof duplex, the Icla-Huamampampa passive roof duplex, and the fault propagation folds branching from the Kirusillas detachment.

In the stage 2, between the cross sections BB' and CC', the shortening in the Kirusillas-Santa Rosa passive roof duplex (curve I) remains constant in spite of the increase of its number of horses. In the set of the "other structures" (curve II), the shortening decreases because the Agua Salada structure and the Icla-Huamampampa passive roof duplex disappear.

The stage 3 is the most interesting because it shows an almost perfect symmetry and an intersection between curves I and II. Between the cross sections CC' and DD', the Kirusillas-Santa Rosa passive roof duplex develops rapidly and occupies the entire foreland thrust belt, whereas the set of the "other structures" dies out and disappears rapidly too. The symmetry and the intersection between the two curves show that stage 3 corresponds to a transfer of displacement. This means that the displacements in the structures that are independent of the Kirusillas-Santa Rosa passive roof duplex were transferred directly to the Kirusillas-Santa Rosa passive roof duplex itself. The area between the cross sections CC' and DD' corresponds to a "transfer zone" in the sense of Dahlstrom [1969]. This zone appears clearly on the map (Figure 9) where, from south to north, the San Antonio Anticline and the Aguaragüe Anticline disappear and leave space for the Charagua Anticline and the Tatarenda Anticline, which are related to the Kirusillas-Santa Rosa passive roof duplex. Curves I and II are not perfectly symmetrical because of a little increase of the total shortening (curve III) that occurred during the displacement transfer.

In the stage 4, between the cross sections DD' and EE', the Kirusillas-Santa Rosa passive roof duplex occupies the entire foreland thrust belt. The total shortening increases slowly (curve II) reflecting

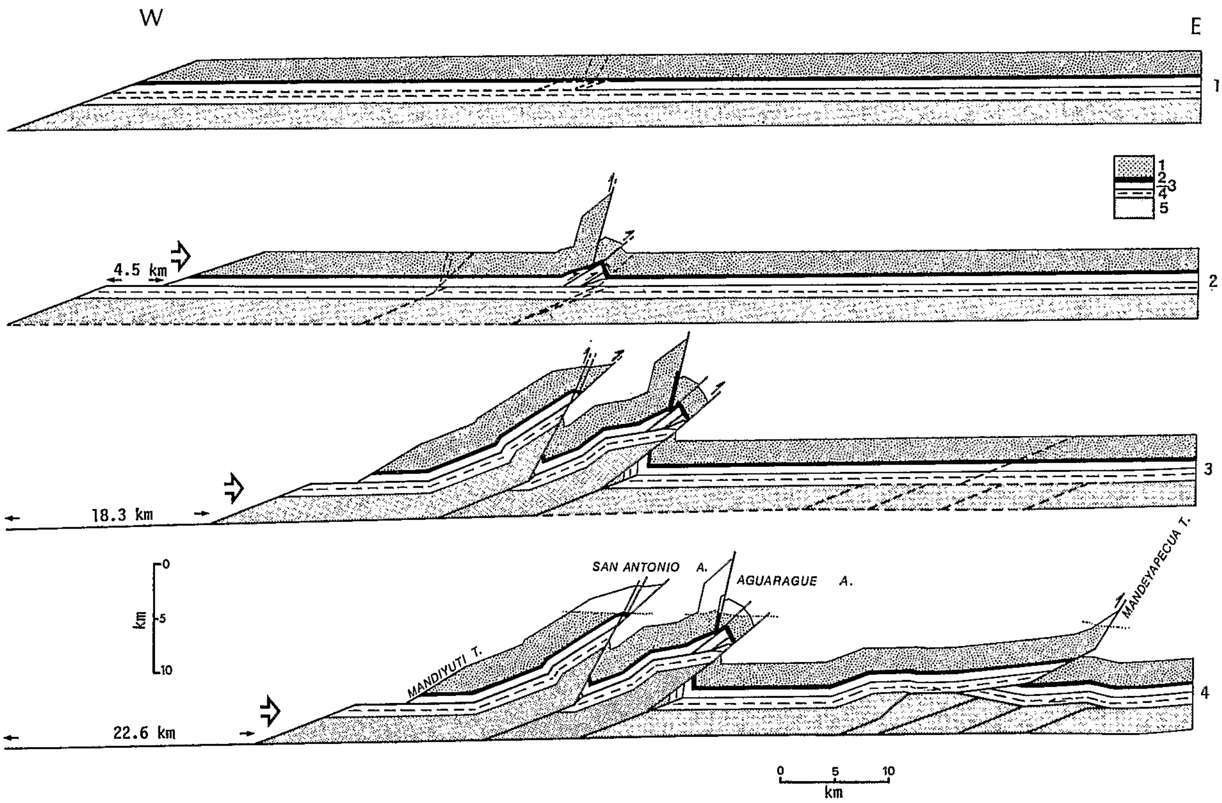

Fig. 12. Schematic deformation sequence proposed for the structural geometry of cross section C-C'. Stratigraphic units are 1, Mesozoic-Permian-Carboniferous; 2, Iquiri Formation; 3, Los Monos Formation; 4, Icla-Huamampampa formations; and 5, Kirusillas-Tarabuco-Santa Rosa formations. T is thrust and A is anticline.

the development of the most internal culmination in the Kirusillas-Santa Rosa passive roof duplex (Tatarenda Anticline).

After calculation of the percentage of the total shortening represented by the shortening in the Kirusillas-Santa Rosa passive roof duplex (curve I, Figure 14) and in the set of the "other structures" (curve II, Figure 14), these two curves appear symmetrical in their entirety. The transfer of displacement from the "other structures" to the Kirusillas-Santa Rosa passive roof duplex begins directly and progressively to the north of the cross section AA'. This transfer is clearly pronounced in the transfer zone defined on the map (Figure 9) between the cross sections CC' and DD', where the two curves are steeper and intersect each other.

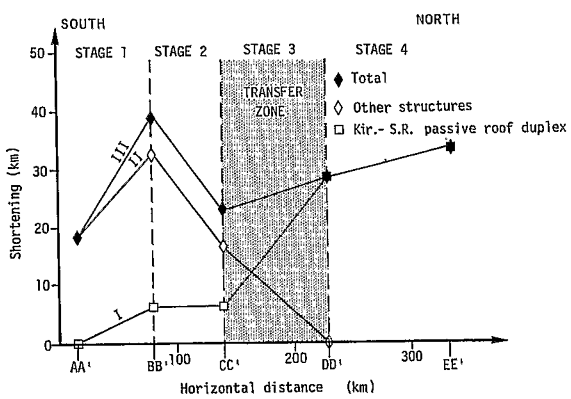

Fig. 13. Variations in amounts of shortening along strike in the Kirusillas-Santa Rosa passive roof duplex (curve I), in the "other structures" of the eastern foreland thrust system (curve II), and in all the eastern foreland thrust system (curve III) of the southern Bolivian Subandean Zone (see text). Kir. S.R. is Kirusillas-Santa Rosa.

From south to north, from the cross section AA' to the cross section DD', the Kirusillas-Santa Rosa passive roof duplex accommodates progressively all the shortening in the foreland thrust system. The other passive roof duplexes and the emergent thrusts are replaced progressively by the blind thrust system of the Kirusillas-Santa Rosa passive roof duplex.

CONCLUSIONS

Discovery and geometric study of passive roof duplexes by cross section balancing in the Subandean Zone of southern Bolivia show again

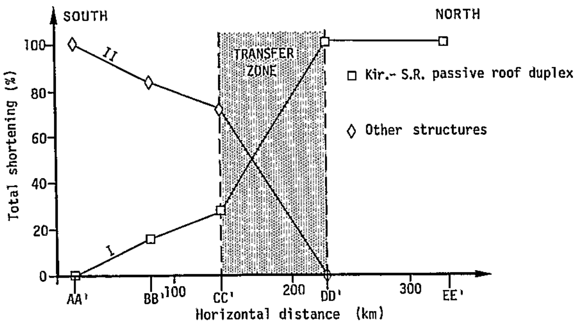

Fig. 14. Variations along strike in the percentage of the total shortening in the eastern foreland thrust system, represented by the shortening in the Kirusillas-Santa Rosa passive roof duplex (curve I) and in the set of the "other structures" (curve II). Kir. S.R. is Kirusillas-Santa Rosa.

the importance of this kind of structure in foreland thrust systems.

The foreland fold and thrust belt of the Subandean Zone of southern Bolivia is largely deformed by passive roof duplexes that can be distinguished by the lithotectonic unit within which duplexing occurred. The roof sequences of these passive roof duplexes are characterized essentially by passive forethrusts. The passive roof duplex developing in the thicker and deeper lithotectonic unit (Kirusillas-Santa Rosa) is the most important; it constitutes the present orogenic front. In the north of the study area (cross sections DD' and EE'), the entire foreland fold and thrust belt is formed by this passive roof duplex. The other passive roof duplexes developed in the Icla-Huamampampa lithotectonic unit and in the Los Monos lithotectonic unit. Apparently, passive roof duplexes propagated toward the foreland from deeper and deeper lithotectonic units.

Assuming that the present orogenic front has developed ultimately, sequential restorations of cross sections AA', BB', and CC' (Figures 10, 11, and 12) show a piggy back sequence of passive roof duplexes. In cross section BB', for example, the sequential restoration (Figure 11) shows the development of three successive passive roof duplexes: the first one appears in the Los Monos lithotectonic unit, the second in the Icla-Huamampampa lithotectonic unit, and the third in the Kirusillas-Santa Rosa lithotectonic unit. As the passive roof duplex developed, the sole thrust stuck, and the major horizontal displacements were then transferred either to out-of-sequence thrusts in the hinterland or to a new sole thrust in a deeper detachment horizon. Therefore during the late Andean orogeny, each passive roof duplex would have corresponded to the orogenic front at one very particular time in the history of the foreland fold and thrust belt.

From south to north, transfers of displacement from the internal structures to the frontal passive roof duplex (Kirusillas-Santa Rosa) have been observed and quantified from the balanced cross sections. A "transfer zone" appears clearly on the map between cross sections CC' and DD' (Figure 9), where, from south to north, two fault propagation folds disappear and leave space for two other anticlines which are related to the frontal passive roof duplex. Available data are insufficient to explain correctly this phenomenon. However, the lateral variation of passive roof duplexes might be controlled by the geometries of preorogenic sedimentary units, which apparently show changes from south to north [Baby et al., 1989; Hérail et al., 1990].

Acknowledgments. We wish to thank the staff of Yacimientos Petrolíferos Fiscales Bolivianos (YPFB) for permission to publish this paper, which is a contribution to the YPFB-ORSTOM convention on the geology of Bolivia. We are grateful to K. Biddle and an anonymous reviewer for their hepful comments.

REFERENCES

Baby, P., Chevauchements dans une zone à structures complexes: la zone nord pyrénéenne ariégeoise - Utilisation de coupes équilibrées et de données sismiques profondes (ECORS Pyrénées), thèse doctorale, 189 pp, Univ. Paul-Sabatier, Toulouse, 1988.

Baby, P., G. Crouzet, M. Specht, J. Déramond, M. Bilotte, and J.E. Debroas, Rôle des paléostructures albo-cénomaniennes dans la géométrie des chevauchements frontaux nord-pyrénéens, *C. R. Acad. Sci.ser. 2,* 306, 307-313, 1988.

Baby, P., G. Hérail, J.M. López, O. López, J. Oller, J. Pareja, T. Sempere, and D. Tufiño, Structure de la Zone Subandine de Bolivie: influence de la géométrie des séries sédimentaires antéorogéniques sur la propagation des chevauchements, *C. R. Acad. Sci. ser. 2,* 309, 1717-1722, 1989.

Banks, C.J. and J. Warburton, "Passive roof" duplex geometry in the frontal structures of the Kirthar and Sulaiman mountains belts, Pakistan, *J. Struct. Geol., 8,* 229-237, 1986.

Boyer S.E. and D. Elliott, Thrust systems, *AAPG Bull., 66,* 1196-1230, 1982.

Charlesworth, H. A. K., and L.G. Gagnon, Intercutaneous wedge, the Triangle Zone, and structural thickening of the Mynheer coal seam at Coal Valley in the Rocky Mountain Foothills of central Alberta, *Bull. Can. Pet. Geol., 33,* 22-30, 1985.

Dahlstrom, C.D.A., Balanced cross sections, *Can. J. Earth Sci., 6,* 743-757, 1969.

Déramond, J., P. Baby, M. Specht, and G. Crouzet, Géométrie des chevauchements dans la Zone nord-pyrénéenne ariégeoise précisée par le profil ECORS, *Bull. Soc. Géol. Fr., 8,* VI, 2, 287-294, 1990.

Dunne, W.M. and D.A. Ferril, Blind thrust systems, *Geology, 16,* 33-36, 1988.

Fallot, P., Les chevauchements intercutanés de Roya, *Ann. Hebert Haug, 7,* 161-169, 1949.

Gordy, P.L., F.R. Frey, and D.K. Norris, Geological guide for the C.S.P.G. and 1977 Waterton-Glacier Park Field Conference, *Can. Soc. Pet. Geol.*, Calgary, Canada, pp. 1-93, 1977.

Hérail, G., P. Baby, M. López, J. Oller, O. López, R. Salinas, T. Sempere, G. Beccar, and H. Toledo, Structure and kinematic evolution of the Subandean thrust system of Bolivia (abstract), in *Symp. Int. "Géodynamique Andine" 1990,* edited by the Institut Français de Recherche Scientifique pour le Développement en Coopération , 179-182, Colloques et Séminaires, Paris, 1990.

Jones, P.B., Oil and gas beneath east-dipping underthrust faults in the Alberta Foothills, Canada, in *Geologic Studies of the Cordilleran Thrust Belt*, edited by Powers et al., pp. 61-74, Rocky Mountain Association of Geologists, Denver, 1982.

Jones, P.B., *Quantitative Geometry of Thrust and Fold Belt Structures, Methods Explor. Ser.*, vol. 6, American Association of Petroleum Geologists, Tulsa, Okla., 1987.

López, J.M., Correlación estratigrafica longitudinal de la Faja Subandina entre las fronteras del Peru y Argentina, *Rep 1906,* Yacimientos Petroliferos Fiscales Bolivianos, Santa Cruz, 1974.

Martinez, C., Structure et évolution de la chaîne andine dans le nord de la Cordillère des Andes de Bolivie, *Trav. Doc. ORSTOM, 119,* 352 pp., 1980.

Morley, C.K., A classification of thrust fronts, *AAPG.Bull., 70,* 12-25, 1986.

Oller, J., Consideraciones generales sobre la geologia y estratigrafia de la Faja Subandina norte, Tesis, 120 pp., Univ. Mayor de San Andres, La Paz, 1986.

Padula, E.L., Valoración de las discordancias en las Sierras Subandinas, *Bol. Tec. YPFB, T1,* 7-28, 1959.

Pareja, J. and R. Ballón, Mapa geológico de Bolivia, scale 1:1,000,000, Yacimientos Petrolíferos Fiscales Bolivianos and Geobol, La Paz, 1978.

Price, R.A., The Cordilleran foreland thrust and fold belt in

the southern Canadian Rocky Mountains, in Thrust and Nappe Tectonics, edited by K.R. McClay and N.J. Price, *Geol. Soc. Spec. Publ. London, 9,* 427-448, 1981.
Roeder, D., Andean-age structure of Eastern Cordillera (Province of La Paz, Bolivia), *Tectonics, 5,* 23-39, 1988.
Sempere, T., G. Hérail, and J. Oller, Los aspectos estructurales y sedimentarios del oroclino boliviano, *Congr. Geol. Chile 5th, vol. 1,* pp. A127-142, Santiago de Chile, 1988.
Sempere, T., G. Hérail, J. Oller and M.G. Bonhomme, Late Oligocene-early Miocene major tectonic crisis and related basins in Bolivia, *Geology, 18,* 946-949, 1990.
Sheffels, B., Deformational style and crustal shortening in the Bolivian Andes (abstract), *Eos Trans., AGU, 67,* 1241, 1986.
Sheffels, B., Structural constraints on crustal shortening in the Bolivian Andes, Ph.D. Thesis, 170 pp., Mass. Inst. of Technol., 1988.
Suppe, P., Imbricated structure of western foothills belt, southcentral Taiwan, *Petr. Geol. Taiwan, 17,* 1-16, 1980.
Suppe, J. and J. Namson, Fault bend origin of frontal folds of the western Taiwan fold-and-thrust belt, *Petr. Geol. Taiwan, 16,* 1-18, 1979.
Vann, I.R., R.H. Graham, and A.B. Hayward, The structure of mountain fronts, *J. Struct. Geol., 8,* 215-227, 1986.
Wines, R.F., Productive duplex imbrication at the Neuquén basin thrust belt front, Argentina, in *Petroleum and Tectonics in Mobile Belts,* edited by J. Letouzey, pp. 69-80, Editions Technip, Paris, 1990.
Woodward, N.B, S.E. Boyer, and J. Suppe, An outline of balanced cross sections, TN, Stud. in Geol., 11, 170 pp., Univ. of Tenn., Dep. of Geol. Sci., Knoxville, 1985.

Baby, P., ORSTOM, CC 4875, Santa Cruz, Bolivia.
Hérail, G., ORSTOM, CP. 9214, La Paz, Bolivia.
Salinas, R., Yacimientos Petroliferos Fiscales Bolivianos, CC. 1659, Santa Cruz, Bolivia.
Sempere, T., ORSTOM, CS de Géologie - Géophysique, 213 Rue La Fayette, 75480 Paris Cedex 10.

(Received December 31, 1990;
revised October 10, 1991;
accepted November 20, 1991.)