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Structural evolution of the Argentine Precordillera: the Rio San Juan section

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Abstract—The Argentine Precordillera (AP) represents a high-level fold-and-thrust belt which was formed during the Andean (Tertiary) crustal shortening. In a W–E transect studied, mostly E-directed imbrications are combined with folding and involve a pile of Cambrian to Tertiary sediments. The thrust belt is detached above a main décollement within the Ordovician to Lower Devonian strata. To the east it is bounded by a back thrust zone directed westwards. Restored sections allow an estimate of crustal shortening and also provide insight into the structural development during pre-Tertiary times. Carbonate platform sequences of Cambrian to Ordovician age grade into a (volcani-)clastic succession with transitional mélanges representing deposits along a western continental slope. In the western and easternmost parts of the AP, Cambrian to Silurian deposits are affected by a first folding which to the west is combined with a slight metamorphic overprint. During Carboniferous to Permian times intensified mobility along the eastern rim and in the western parts of the AP leads to crustal extension which partly was triggered by the formation of synsedimentary normal faults. In the central AP no angular unconformities at the base of Carboniferous–Permian deposits were found. There was no field evidence found to postulate a terrane boundary within the AP area, and an onset of thrust tectonics during Cretaceous to Early Tertiary times.

GEOLOGICAL SITUATION

The 'thin-skinned' thrust-and-fold belt of the Argentine Precordillera (AP) forms a N–S mountain chain, about 400 km long and 80 km wide (Fig. 1), with a maximum elevation of more than 4000 m above sea level. It is composed of a thick sequence of Early to Late Palaeozoic sediments whilst Mesozoic deposits are mainly preserved in basin structures along the western and eastern margins. Late Tertiary clastic sediments with volcanic intercalations (Leveratto 1968, 1976, Bercowski & Figueroa 1987, Johnson *et al.* 1987, Jordan *et al.* 1990) fill some intra-montaneous basins (e.g. Jordan *et al.* 1990), the large-scale N–S-trending foreland basin along the eastern margin (e.g. Beer & Jordan 1989, Beer 1990), and the Uspallata–Calingasta–Iglesia basin to the west (Beer *et al.* 1990) separating the AP from the Frontal Cordillera.

Several authors have depicted the structural style of deformation which is generally characterized by N–S-striking imbricate faults verging eastwards (e.g. Heim 1952, Baldis & Chebli 1969, Ortiz & Zambrano 1981, Baldis *et al.* 1982, Zambrano 1985). They affect the whole Palaeozoic pile of sediments as well as the Tertiary deposits. The intense thrust tectonics was explained to have been triggered by a flat segment of the Nazca plate subducting eastwards under the South American plate (Jordan *et al.* 1983).

The Early to Late Palaeozoic evolution is interpreted to result from a subduction process of the Palaeo-Pacific crust below the present western margin of Gondwana with the 'Chilenia' Terrane having subsequently collided with the so-called 'Proto-Precordillera' during Palaeozoic times (compare Ramos *et al.* 1984, 1986, Ramos 1988). Basalt flows occur along the western margin of the AP. Ramos (1988) concluded that they represent relics of an older ocean basin which was incorporated into the subduction complex. The Precordillera itself is thought to represent a displaced terrane (Baldis *et al.* 1988, Ramos 1988) having been transported along major strike-slip faults through the whole South American part of Gondwana during Early Palaeozoic times (Baldis *et al.* 1988).

The interpretations and plate tectonic reconstructions summarized above are distinct from the structural evolution during Cenozoic times. However, no clear description was found in the literature to separate Tertiary from earlier formed fabrics. To elucidate the pre-Tertiary configuration there exist a few attempts to restore sections across the Subandean chain (northern Argentina) or the AP (compare Allmendinger *et al.* 1983, 1990, and Sarewitz 1988).

The present study is based on structural investigations along two W–E sections forming a transect across the AP. For this purpose the Rio San Juan valley was chosen (Fig. 1) because it is most accessible. The analyses are based on maps which were drawn from interpretations of aerial photographs combined with field mapping. The aim of this paper is to describe the structural evolution, to understand the mechanisms of crustal shortening, to estimate the minimum amounts of shortening across the AP, and to give insights into the pre-Tertiary evolution. Section reconstructions are based on surface data only as, up to now, subsurface data (seismic, drilling) are not available. In the text, cleavage planes and shear planes are abbreviated with *S* and *C*, respectively. Additional subscripts T and P refer to Tertiary and Palaeozoic fabrics, respectively.

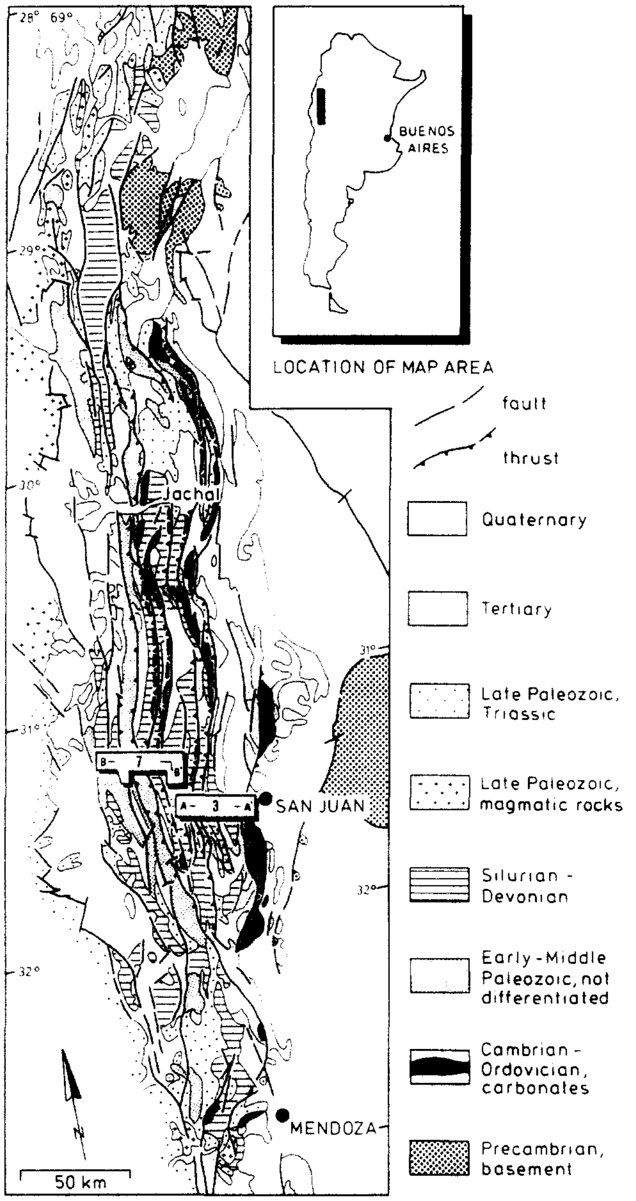

Fig. 1. Geological sketch map of the Precordillera (Argentina), compiled and adapted after Baldis *et al.* (1982) and own investigations. Location of study area is shown by block insets which represent maps, Figs. 3 and 7.

STRATIGRAPHY

No Precambrian basement rocks are exposed in the Argentine Precordillera (AP). It is highly probable that the basement is composed of metamorphic rocks which can be inferred from xenoliths found in Tertiary volcanics.

In the eastern AP, the Cambrian to Ordovician platform deposits consist of a pile of carbonate rocks, at least 2500 m thick, comprising the La Laja, Zonda, La Flecha and San Juan Formations (Fig. 2) (compare Bordonaro 1980, Baldis & Bordonaro 1984). In contrast, the western equivalents of the carbonate platform consist of a monotonous sequence of meta-sediments (Don Polo Formation), probably Cambrian to Ordovician in age, but not well constrained stratigraphically (Turco Greco & Zardini 1984). Graptolite findings indicate that Ordovician meta-sediments also occur in the Sierra del Tontal (Portezuelo Tontal Formation; Cuerda *et al.* 1985a). Again proved by graptolites, the Alcaparrosa Formation of the western AP seems to be partly of Caradocian age (e.g. Amos *et al.* 1971, Aparicio & Cuerda 1976, Kerllenevich & Cuerda 1986). It contains basic volcanics which are largely made of pillow lavas and may represent volcanic flows on a former ocean floor.

After a hiatus, indicated by a thin conglomeratic horizon, the carbonate platform of the study area is conformably overlain by sandstones, shales and siltstones, with minor carbonate intercalations (Tambolar and Talacasto Formations; compare Baldis 1975). The stratigraphic gap is not fully understood. It might however span the post-Arenigian to Lower Silurian interval (Fig. 2).

Along the eastern rim of the AP, several occurrences of clastic deposits (Rinconada Formation s.l.) span the Ordovician to possibly Lower Devonian interval (Levy & Nullo 1974, Amos & Fernandez 1977, Cuerda 1981, 1985, Peralta 1984, 1985, Peralta & Medina 1985, Peralta & Uliarte 1985, Sarmiento 1985). Parts of these sequences contain huge blocks of carbonates, sandstones and conglomerates, and are interpreted to represent mélange deposits. However, the genetic interpretation of the clasts is still debated (tectonic vs sedimentary origin: compare e.g. Heim 1948, Amos & Fernandez 1977).

Counterparts of the mélange deposits can be found in the western part of the AP (Sierra del Tontal). The so-called Los Sombreros Formation is interpreted as representing the slope facies (Fernandez *et al.* 1987, Banchig & Bordonaro 1990, Banchig *et al.* 1990) between the Early Palaeozoic carbonate platform to the east and the clastic plus volcanic basin deposits to the west. Fossil findings suggest that this sedimentary mélange could be Middle Cambrian to Ordovician in age (Cuerda *et al.* 1983, 1985a,b).

In the Rio San Juan section, the Silurian to Lower Devonian sediments are conformably overlain by dark sandstones with thin siltstone layers (Punta Negra Formation) which represent the Middle to Upper Devonian interval. Towards the west they become more flysch-like with fine-grained siltstone layers increasing in abundance and thickness (see also Gonzalez Bonorino 1975). In the western part of the section, to the south and west of km 114 of the main road in the valley, comparable sequences occur which shall be interpreted to be also Devonian in age.

These rocks, and also Ordovician meta-clastics to the east, are unconformably overlain by dark conglomerates, sandstones, and siltstones which obviously represent deposits of Carboniferous age. For the km 114 area, different opinions exist with respect to the ages, names and lateral distributions of the different Devonian, Late Palaeozoic and Triassic formations (compare Kerllenevich 1967, Amos *et al.* 1971, Venturini 1980, Sessarego 1983, Selles Martinez 1985, Stinco 1985). Hence, here local names are avoided and the descriptions refer to the most probable age relationships and areal distributions studied in the field.

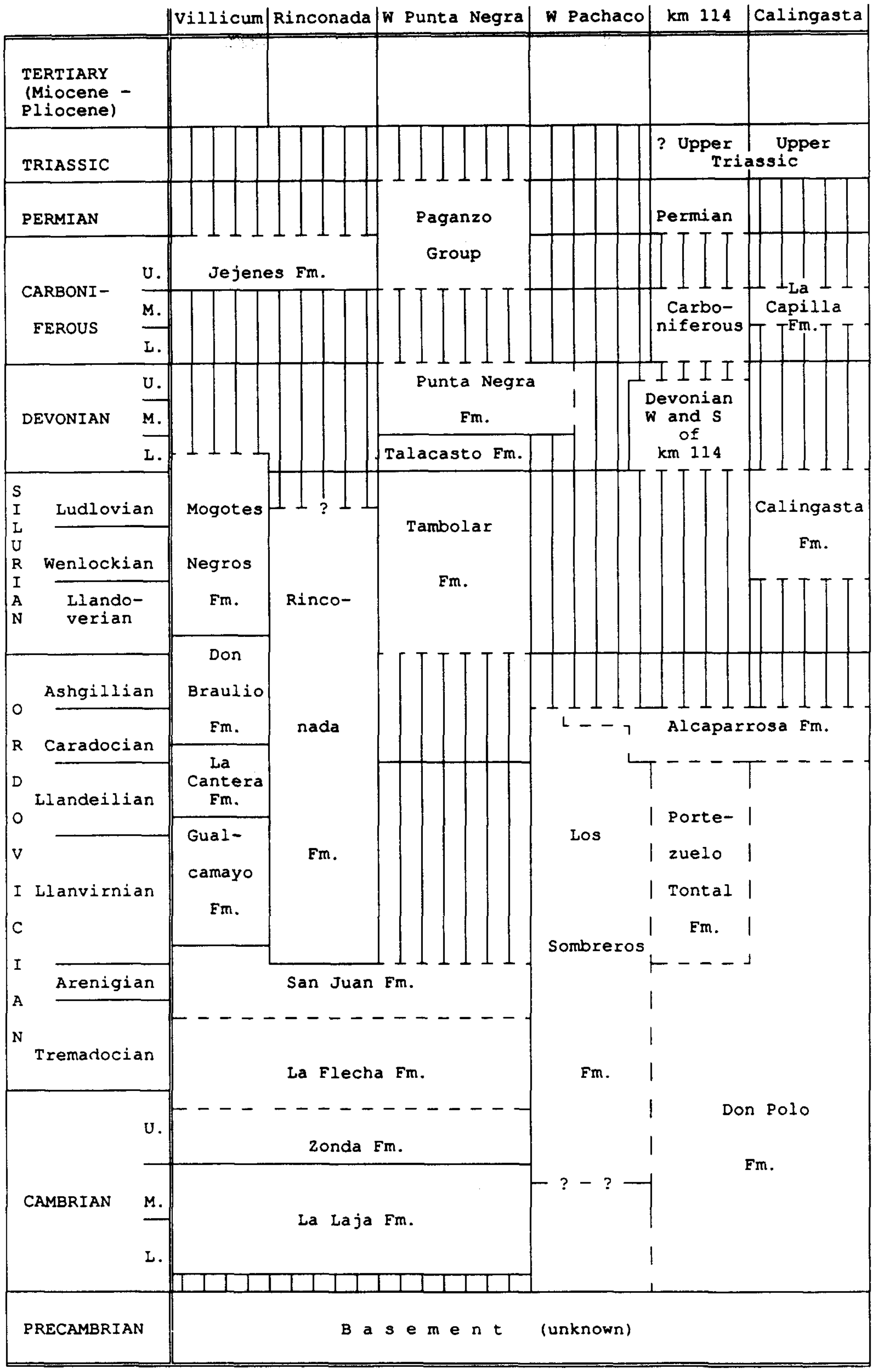

Fig. 2. Stratigraphic chart of Palaeozoic to Tertiary Formations of the Precordillera for the Rio San Juan section, including data from adjacent areas; compilation based on authors cited in text.

West of km 114, the Carboniferous rocks (Azcuy *et al.* 1981) unconformably overlie sandstones of probably Devonian age. They are in turn overlain by a white to red coloured (cross-bedded) sandstone sequence which may represent the Permian. Again these rocks are also unconformably covered by a Triassic sandstone sequence.

The situation in the km 114 area can be compared with the eastern margin of the AP (Zonda chain) where the Upper Carboniferous Jejenes Formation (Arrondo 1971, Cesari *et al.* 1985) is bounded by a basal angular unconformity. However, it clearly contrasts with the Upper Carboniferous to Permian conglomerate plus sandstone sequence to the west (Paganzo Group: Fig. 2) which overlie the Devonian Punta Negra Formation above an erosional disconformity. There, Late Tertiary

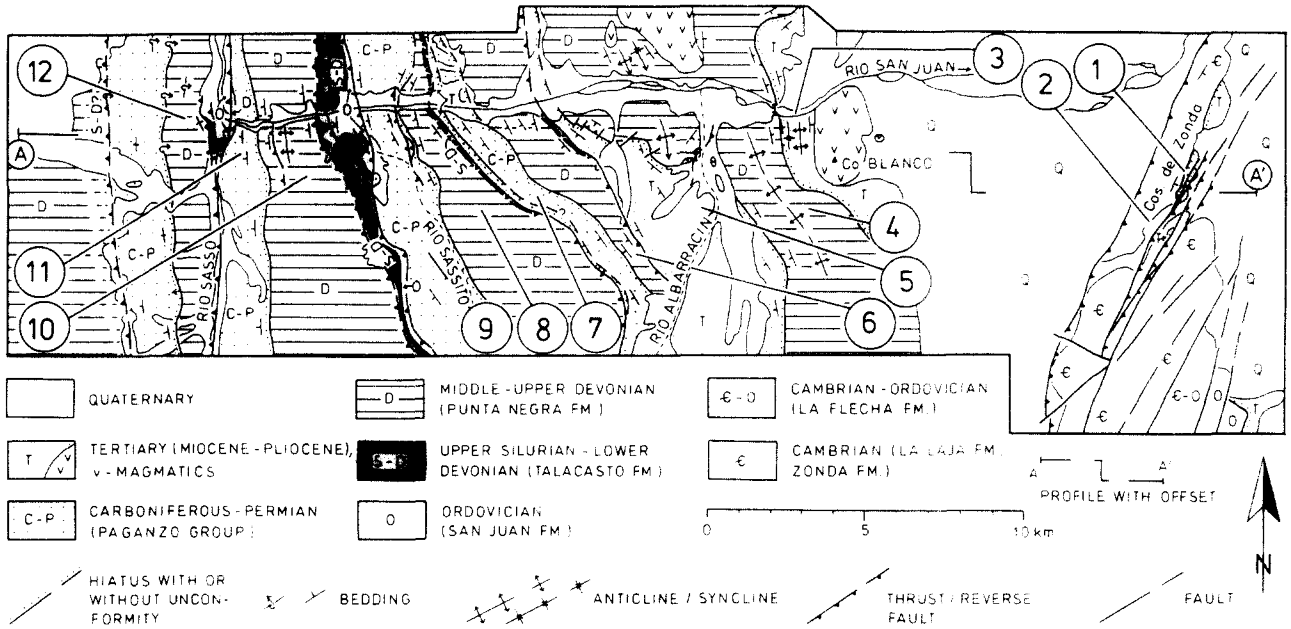

Fig. 3. Geological sketch map of the eastern part of the Rio San Juan section including the Zonda chain (Eastern Precordillera), based on field mapping and interpreted aerial photographs; eastern parts partly after Leveratto (1968) and Baldis & Bordonaro (1984). Encircled numbers show locality of the fabrics shown in Fig. 15(a). A–A′ is the line of section for Fig. 4.

sediments with volcanic intercalations conformably overlie Devonian or Late Palaeozoic deposits. In the western parts, however, they are separated by a basal angular unconformity.

THRUST TECTONICS

In the whole E–W transect across the AP, structures typical of a thin-skinned mode of crustal shortening within foreland thrust belts occur (Bally *et al.* 1966, Price & Mountjoy 1970, Price 1981, 1986, Boyer & Elliott 1982). In the eastern section (Figs. 3 and 4), imbricate faults dipping to the west displace Upper Silurian to Permo-Carboniferous strata. Tertiary deposits on top of the eastern thrust sheets are also involved. The imbricates formed above a main décollement which truncates the more incompetent sand- and siltstones of the Upper Silurian to Lower Devonian. In the western parts of the section, the uppermost parts of the Ordovician carbonates (San Juan Formation) form the base of the imbricates (Fig. 5a).

Towards the west, the dip of the imbricate thrust surfaces increases with the westernmost fault planes standing vertical or being overturned (Figs. 4 and 5b). Towards the north of the profile, east of the N–S-trending part of the Rio San Juan, the steepened to overturned sequence continues. This east to west steepening of the imbricates can be explained by a progressive migration of already stacked western imbricates along the main décollement. This implies a 'piggy back' mode in passively carrying earlier-formed imbricated thrust sheets above a basal décollement which propagated eastwards. Younger imbricate faults formed in front of the stack of imbricates, while the earlier-formed imbricates continued their movements along the pre-existing thrust faults which were steepened or overturned. This interpretation is confirmed by the later-formed fabrics found in the imbricates of the central AP.

Imbrications of Ordovician to Devonian strata also occur in the western part of the AP where Tertiary sediments are preserved on top of the Devonian strata in the Pachaco area (Figs. 7 and 8). There, thicker carbonate sequences of Ordovician age form the bases of two imbricate sheets indicating a deeper position of the main décollement. They are doubled by an imbricate fault, and the western carbonates are overlain by Silurian to Devonian rocks. The western margin of this intensely folded Devonian sequence is marked by a contact with underlying Ordovician siltstones which form a broad anticlinal structure. I interpret this contact to be of sedimentary origin as no indications were found to infer a fault line. Although no fossil findings prove an Ordovician age of the underlying sequence, its lithologic composition with basic volcanics (with pillow lavas at one locality), quartzites and black slates make it quite comparable with the Alcaparrosa Formation (Caradocian) of the western AP.

Above an angular unconformity, dark conglomerates and siltstones overlie the Ordovician sequence to the west of Pachaco. They contain pebbles of basic volcanics and are folded around a large syncline with the underlying Ordovician strata to the south lying on the top of the overturned unconformity. As for the comparable sequence in the km 114 area, I consider these clastics to be of Carboniferous age.

To the east of Q. de los Ratones (Fig. 7), these strata in turn are overthrust by an Ordovician sequence containing a thick limestone layer at the base. The carbonates are laterally reduced to a thin slice within the thrust

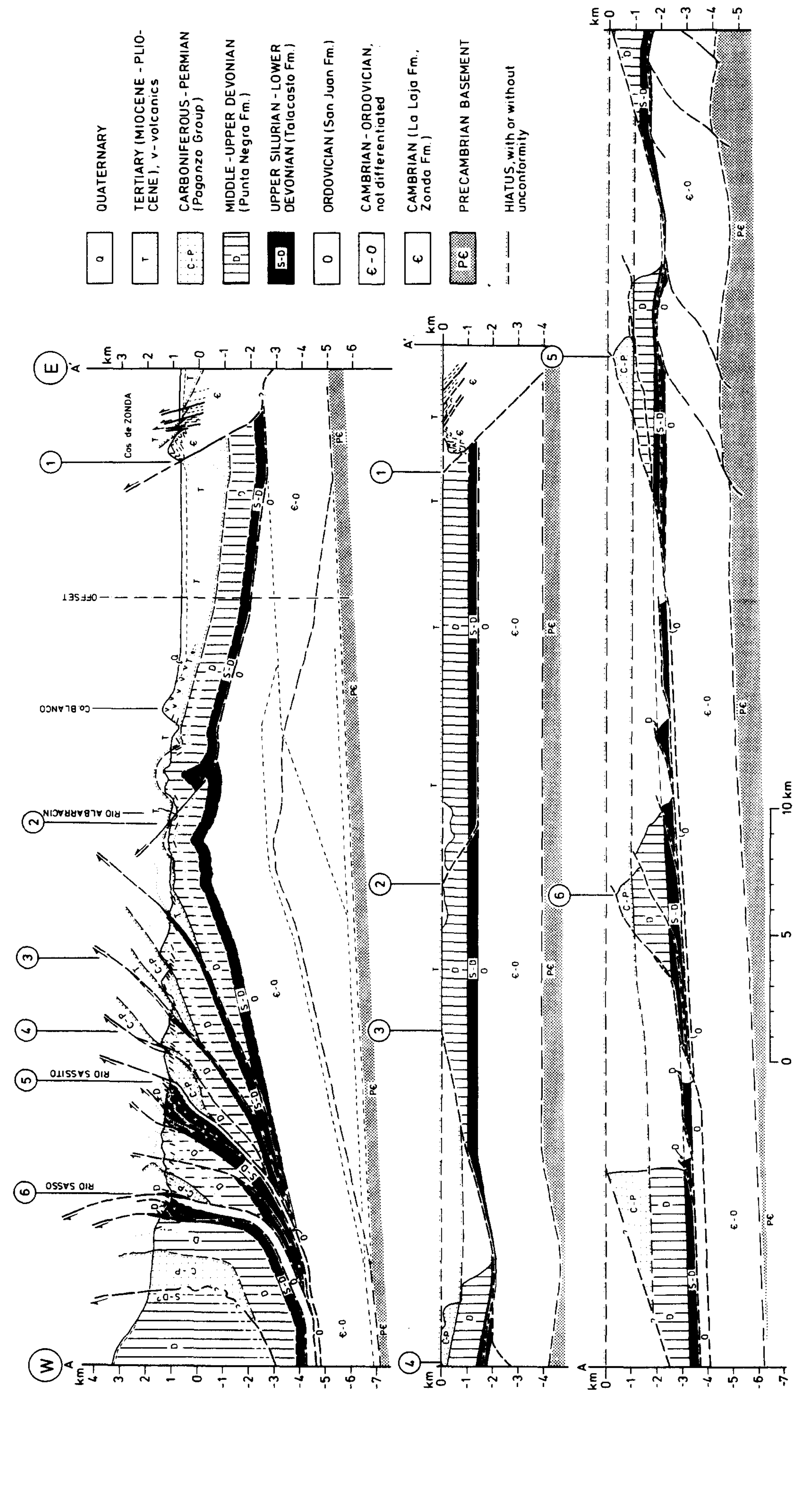

Fig. 4. Interpretative section across the eastern part of the Precordillera (Rio San Juan section); for location see Fig. 3. Top, interpreted section based on surface data. Thick dashed line in the subsurface is the inferred base of the Cambrian to Ordovician carbonate sequence. Thin dashed lines, alternative interpretation with a duplex structure below the anticline. Bottom, restored E–W section (see text for further explanations).

zone, and it seems reasonable to suggest that they could represent the western parts of the truncated carbonate platform. They are overlain by a clastic sequence which, towards the west, contains basic volcanics and also mélange deposits. The latter are exposed to the south of the research area.

Bordering the Sierra del Tontal to the east, there is a steeply inclined thrust zone carrying a monotonous pile of Cambro-Ordovician meta-clastics on the Ordovician sequence (Qda. de Los Ratones; Figs. 7 and 8). In the Sierra del Tontal, the Cambro-Ordovician sequence stands vertical or is overturned. In the western part of the Sierra, it is overlain by Ordovician clastics. The western boundary of the Sierra del Tontal range is marked by a steeply inclined back thrust zone carrying the Ordovician plus underlying Cambro-Ordovician pile of rocks on the Late Palaeozoic and Tertiary strata which cover the km 114 area around the Rio San Juan and to the south (Figs. 7–9). The Late Palaeozoic and Tertiary sequences are gently folded, and a slice of Cambro-Ordovician strata to the south is back thrust on a Permian sequence (Figs. 7 and 9).

Imbricate faults dipping westwards limit the km 114 area to the west. They carry Cambro-Ordovician and Ordovician meta-clastics with basic volcanics towards the east overriding Devonian and Carboniferous deposits in the Rio San Juan area (Figs. 7–9). In turn, they are overthrust by Devonian and Cambro-Ordovician clastics which form the western imbricates (Figs. 5c, 7 and 8). On a major back thrust, near the western border of the AP, Cambro-Ordovician meta-clastics overthrust the Ordovician Alcaparrosa Formation (Caradocian) which largely consists of pillow lavas.

INTERNAL DEFORMATION OF THE THRUST SHEETS

Thrust planes

The mechanical anisotropy of the layered strata plays an important role in the development of folds, thrusts and also of the major décollement zone. The thrusts often follow bedding and, at the scale of several metres, they ramp into higher strata (Fig. 10a).

Layer-parallel slip is a common feature within the different strata as revealed by slickensides on bedding planes (S_0) as well as by gouge zones up to several cm thick. Slickensides display E-directed movements of the hanging wall. These also record E-directed transport along imbricate faults and a W-directed advance of back thrust slices (Fig. 11a). No indications for a stretching perpendicular to the regional strike were found.

The amounts of bedding-parallel displacement are unknown, and hence the thickening of the sedimentary pile within the thrust sheets is difficult to estimate. However, one example of a displaced basalt dyke within Punta Negra sandstones (Fig. 10b) suggests that the amount of lateral gliding has not exceeded more than a few metres. An opposite sense of displacement, suggesting W-directed extension (Fig. 10b), is probably due to an irregular intrusion of the basalt dyke along bedding planes and opened joints perpendicular to bedding. Such a 'staircase-like' dyke was found at another locality without bedding-parallel displacements.

Thrusting can be accommodated by the formation of duplex structures on a dm- to tens of m-scale (Figs. 10a & c), indicating that large amounts of lateral shortening are concentrated within thinner rock packages with respect to the thick imbricate sheets. All the duplexes found are of the hinterland-dipping type.

At the base of the Carboniferous deposits to the east of Rio Sassito, the stratigraphic pile is truncated by different imbricate faults on a tens of m-scale. There, E-directed thrusting results in the generation of oblique ramps which join the hangingwall thrust (Fig. 12). In general, the picture of large-scale diverging splay faults results. This indicates that E-directed thrusting on the map scale was not only controlled by N–S fault lines but that oblique imbricate faults also occur.

Folds

Flexural-slip folding (F_{T1}) occurs on flats as well as at ramp structures. On different scales, the floors of ramp structures show fault-bend folds (Fig. 10b) forming 'ramp-related anticlinal structures' (Mitra 1990). The thrust propagated as a bedding-parallel flat. Locally, fault-propagation folds are translated with the thrust cutting up-sequence into the undeformed sediment. There, the thrust can end as a blind thrust or it can be combined with a second fault-propagation fold in a higher horizon.

Exposed imbricate faults often record drag folds at the base of the overriding thrust sheet (Fig. 13a). Folding can be limited to distinct parts along the thrust plane. In addition, small-scale thrust planes accommodate lateral compression at limbs and/or hinge zones of anticlines and synclines.

On flats, a few flexural-slip detachment folds exhibit an overall box-fold geometry (Fig. 13b) indicating an accommodation of lateral shortening above a bedding-parallel décollement. Such folds sometimes also occur at imbricate faults (Fig. 13c) and these seem to be translated upwards from a bedding-parallel décollement to the steepening fault plane.

The base of imbricate sheets shows evidence of intense folding and/or shearing (Fig. 14). There, both underlying and overriding strata can be folded around cm- to m-scaled flexural-slip F_{T1}-folds with curving axes. Comparable features can also be seen in the oblique ramp structures where disrupted slices of Devonian and Carboniferous rocks on a tens of m-scale are folded between thrust planes. Fold axes are parallel to the oblique imbricate faults and thus follow the curving of the imbricates (Fig. 12).

Cleavage and shear planes

S_{T1} fracture cleavage planes cut across the bedding at high angles and are related to F_{T1}-folds. Within shaly

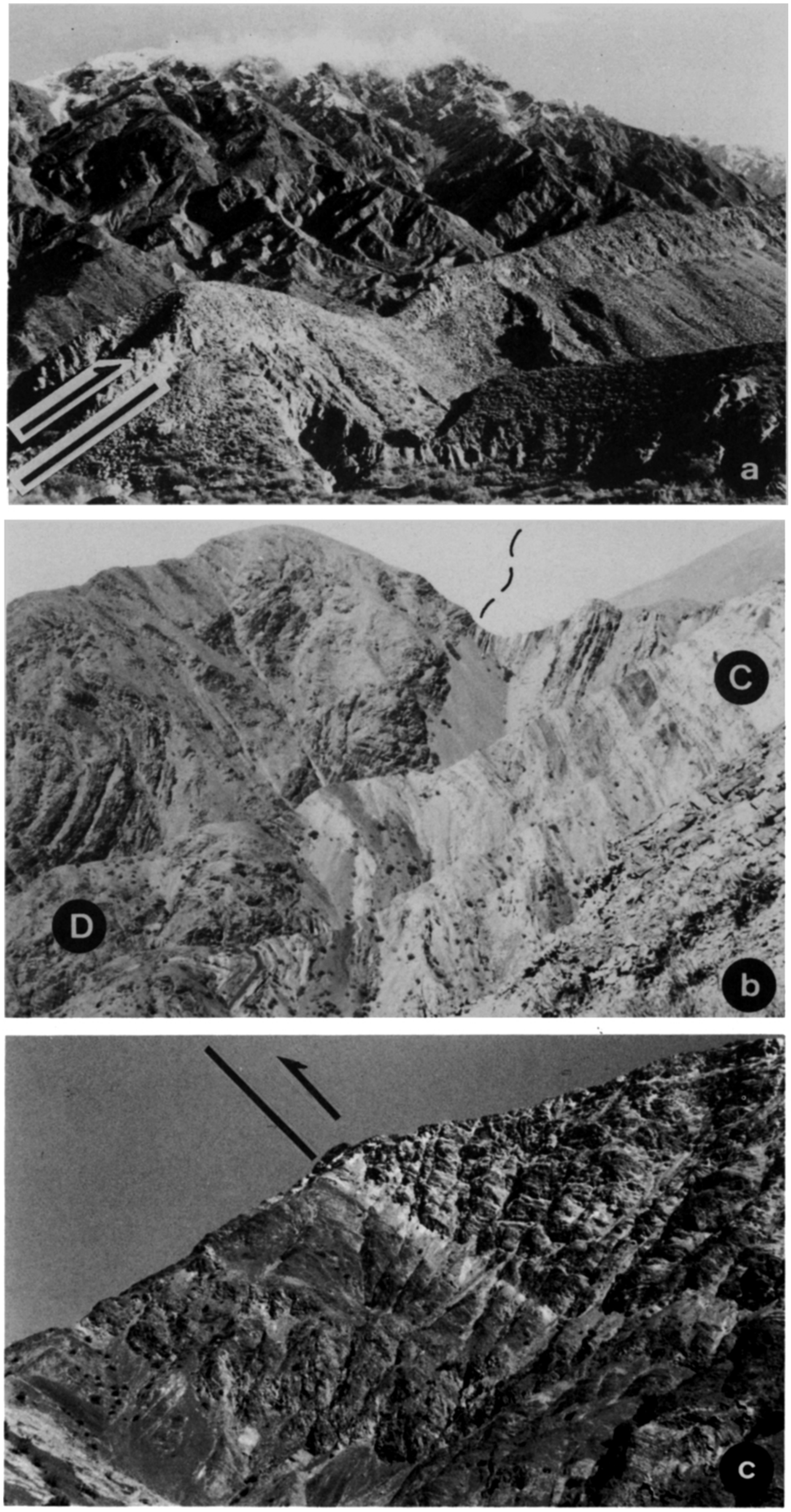

Fig. 5. (a) Base of imbricate sheet to the north of Rio San Juan (west of Rio Sassito, view to the north). Ordovician limestone (centre, light) and Silurian–Devonian sequences (background, dark) are thrust (shown by arrow) upon Carboniferous–Permian sandstones (foreground, partly covered by Quaternary deposits). (b) Steeply inclined to overturned imbricate sheet with a sedimentary contact (dashed line) between Devonian sequence (D) and Carboniferous–Permian strata (C). Note F_{T1}-folding due to thrust tectonics directed eastwards (left) (Rio Uruguay, N–S-trending part of Rio San Juan, view toward the south). (c) Ordovician sequence (left) dipping eastwards is overthrust by (?) Cambrian–Ordovician metaclastics of the Don Polo Formation (Rio San Juan valley west of km 114, view toward the southwest).

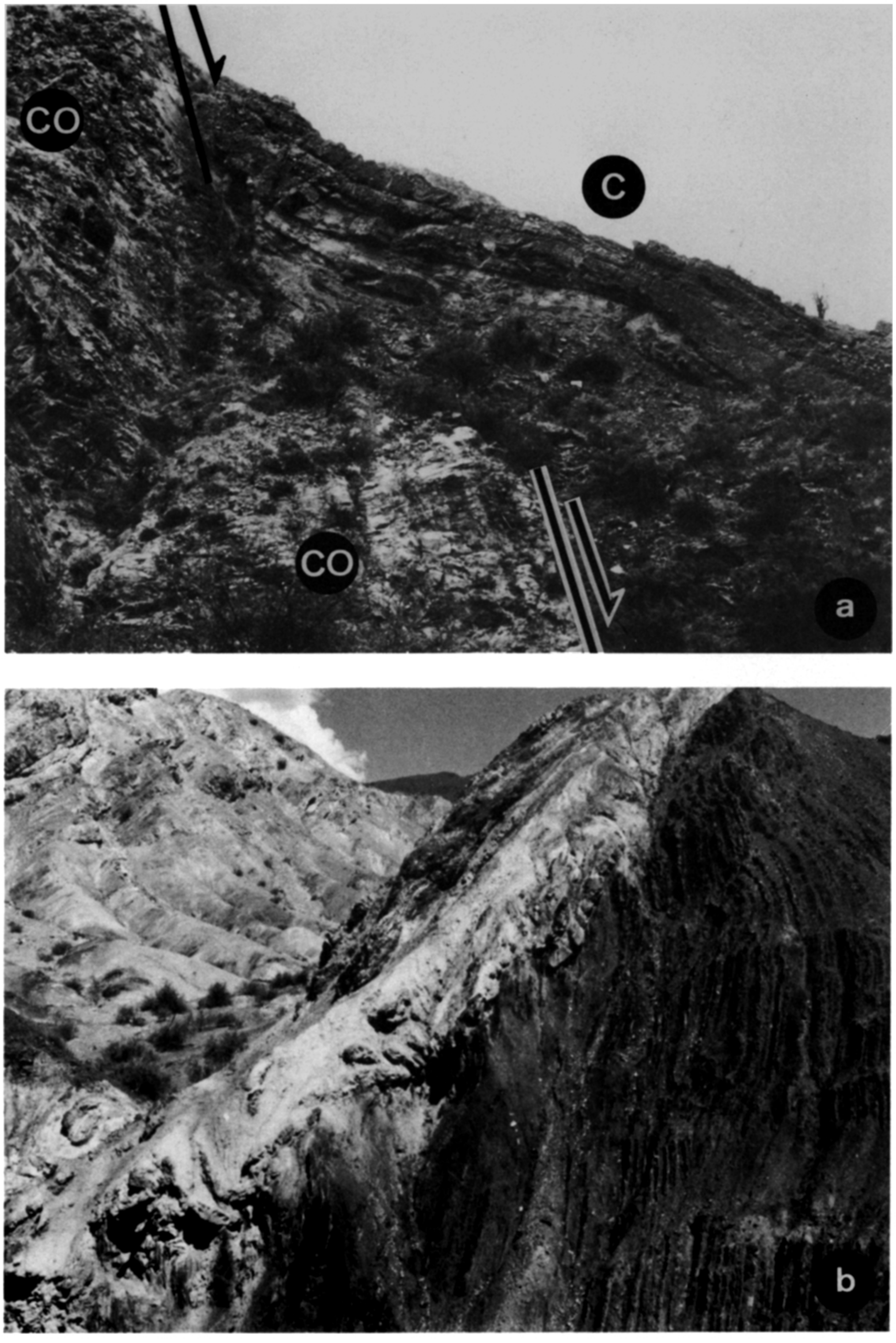

Fig. 6. (a) Synsedimentary normal faults dipping eastwards displace Cambro-Ordovician carbonates (CO) and are partly covered by Carboniferous (C) conglomerates, breccias and sandstones (Quebrada Las Lajas, eastern rim of the Precordillera, view toward the north, height of the outcrop ≈15m). (b) Angular unconformity between Carboniferous siltstones and conglomerates (right) and Permian sandstones (white, left). Note folding of Permian strata and the contact plane due to W–E shortening during Tertiary times (south of km 114, view toward the south, height of the outcrop ≈20 m).

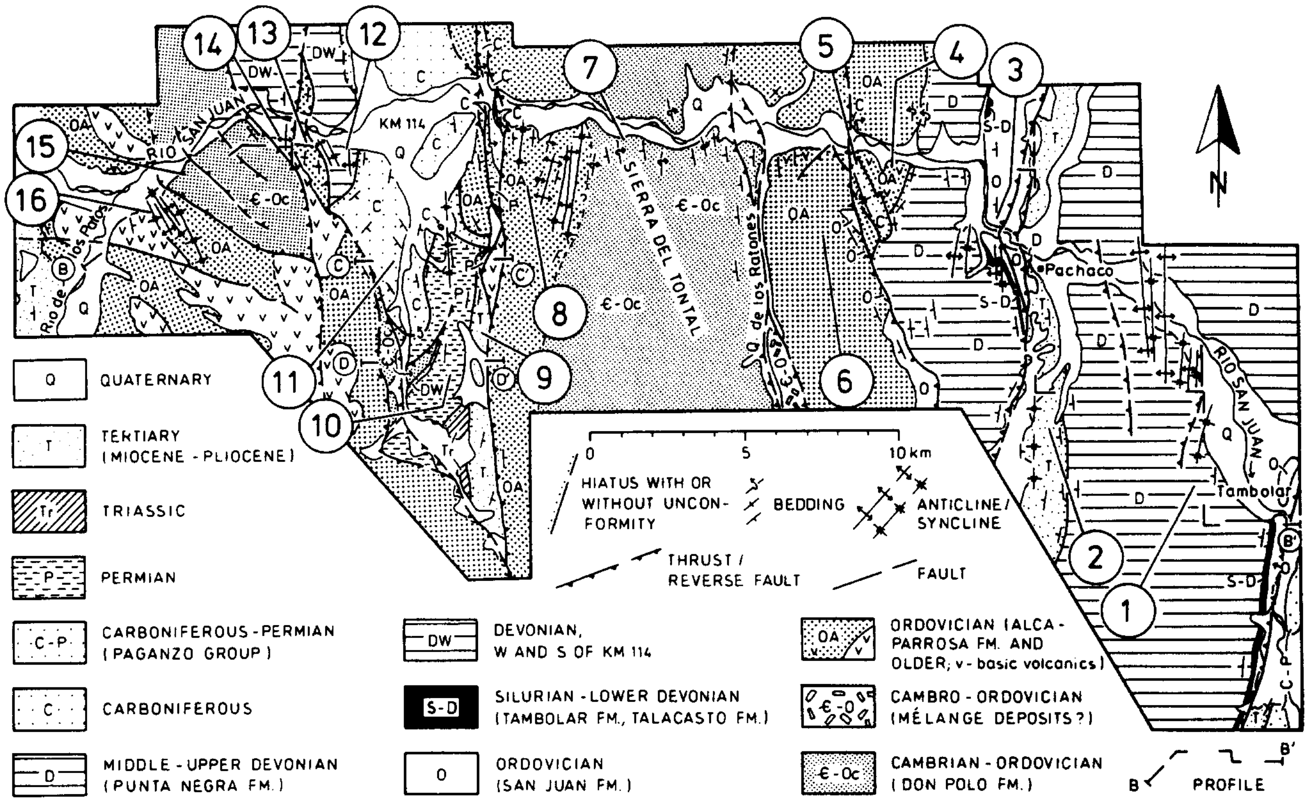

Fig. 7. Geological sketch map of the western part of the Rio San Juan section based on field mapping and interpreted aerial photographs. Encircled numbers refer to localities of the fabrics in Fig. 15(b). B–B′ is the line of section for Fig. 8. C–C′ and D–D′ are sections in Fig. 9.

and silty layers, S_{T1}-planes are closely spaced whereas in sandy layers widely spaced cleavage planes occur. Both plane sets often fan around the hinge zones of F_{T1}-folds (Figs. 13 and 14). On flats, widely-spaced cleavage planes are oriented more or less perpendicular to bedding planes (Fig. 10b).

F_{T1}-folding and S_{T1}-cleavage formation are accompanied by the generation of C_{T1}-shear planes. These strike N–S (Fig. 11b) and mostly record an E-directed layer-parallel shear (Figs. 13a & b) as revealed by slickensides and/or striae on bedding planes. C_{T1}-planes can climb up-bedding at different angles and join another bedding-parallel shear plane in the hangingwall. Thus, both plane sets create lens-shaped fabrics on a cm- to m-scale.

It is noteworthy that S_{T1}-cleavage planes and C_{T1}-shear planes are part of the same D_{T1} event as imbricate faults develop from such shear planes (Figs. 10a and 13a) or shear plane sets generate between imbricate faults (Figs. 13a & b). On the other hand, S_{T1}-cleavage planes can concentrate towards imbricate faults, and, adjacent to the fault line, they are closely spaced (Fig. 14), and become indistinguishable from the C_{T1}-shear planes.

The coexistence of both S_{T1}- and C_{T1}-planes, on flats being oriented perpendicular to each other, could be explained by a conjugate plane set which can be found at different localities. Within silty layers, S_{T1}-cleavage planes consist of a conjugate set with an opposite sense of shear along both planes. One of the planes might further develop as a C_{T1}-shear plane and/or as an imbricate fault with an E-directed overall sense of displacement whilst the others remain as S_{T1}-cleavage planes.

Sets of C_{T1}-shear planes, dipping to the east and west, could also be observed in the western Precordillera. They partly represent a conjugate plane set recording an E–W horizontal compression. The shear planes can be combined with conjugate sets of reverse faults. These simultaneously growing thrusts and back thrusts enhance the tectonic wedging process.

C_{T1} shearing can be seen at the boundaries between different lithologies where there are competence contrasts. There, the planes form lens-shaped fabrics which can develop as small-scale duplexes. At a few localities, C_{T1}-planes, climbing up-sequence, are combined with second-order shear planes which dip eastwards and cut down-sequence. The latter record a comparable sense of shear (top-to-the-east). It is possible to explain these shear planes as synthetic Riedel shears supporting the overall sense of displacement.

Within Tertiary sediments, layer-parallel shear accommodates the bending of the sequence below a back thrust at the southern rim of the Sierra de Villicum. Between the bedding-parallel shear planes, smaller-scaled second-order shear planes occur which display an opposite sense of shear. The plane set seems to have supported the bending of the sediments.

Continuing horizontal compression is then accomplished by a third set of conjugate shear planes dipping eastwards and westwards. These record an opposite sense of shear and cut across the pre-existing plane set.

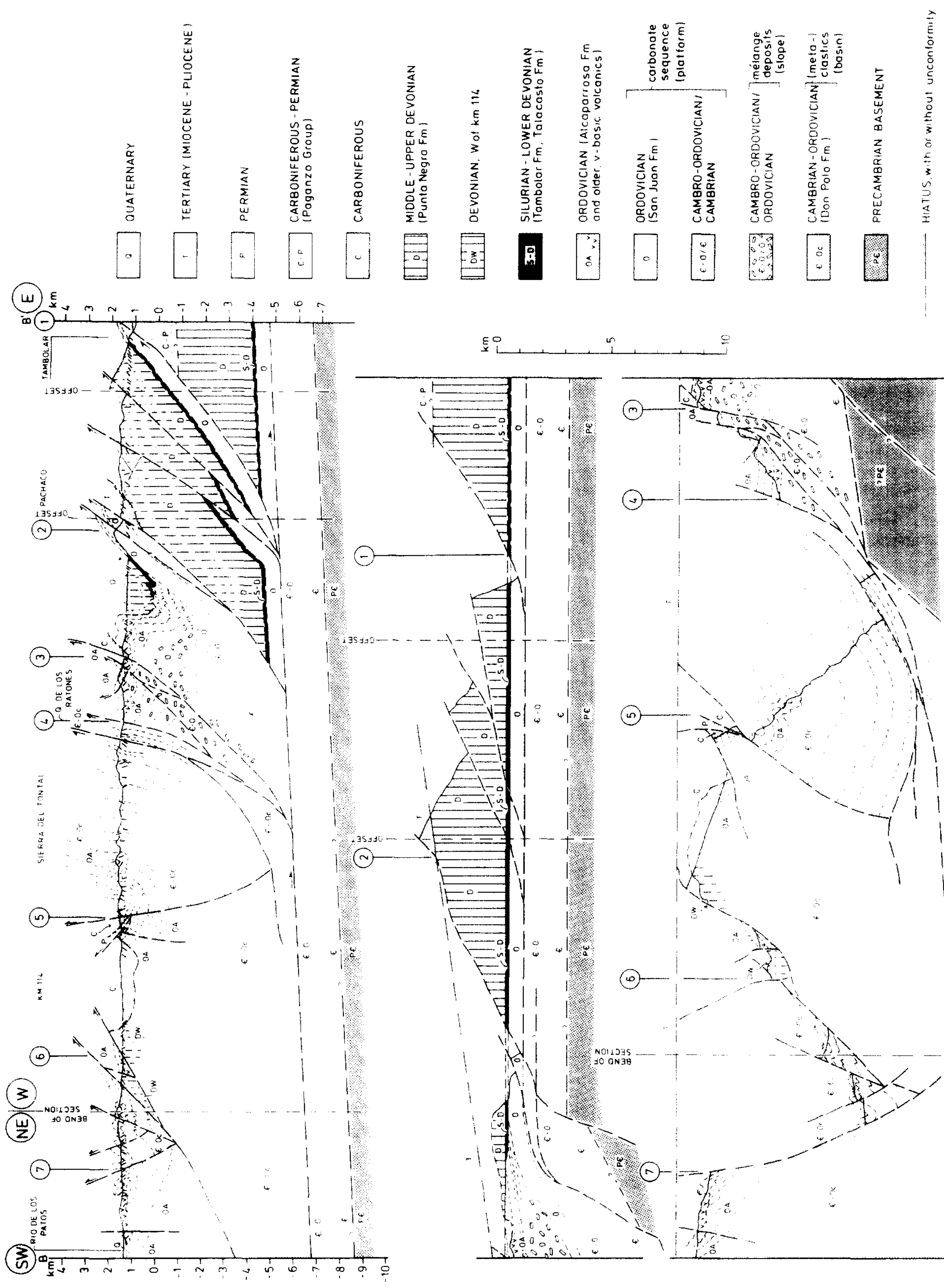

Fig. 8. Interpretative profile across the western part of the Precordillera (Rio San Juan section); for location see Fig. 7. Top, interpreted section based on surface data. Bottom, restored E–W section; interpretations of the western part are based on minimum displacements along thrust faults.

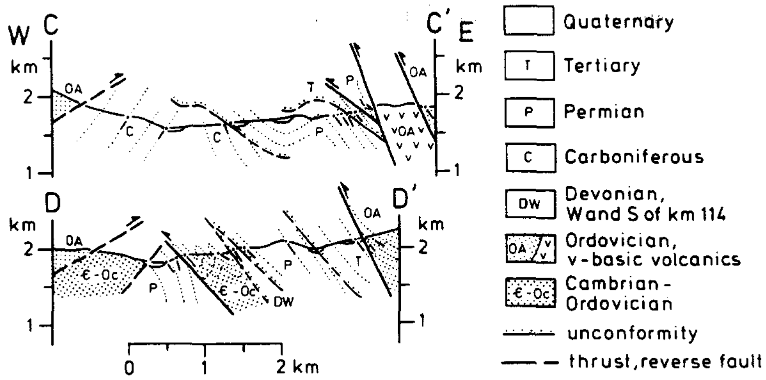

Fig. 9. W–E profiles across the Palaeozoic to Tertiary sequences south of km 114 (for locations see Fig. 7).

All this suggests that during the first deformational event horizontal compression can be accommodated by a variety of shear planes. These generate with respect to the different lithologies and orientations of the fault traces.

In the thrust belt, B_{T1}-fold axes, S_{T1}-cleavage planes, C_{T1}-shear planes and thrust planes strike more or less N–S (Fig. 15). Curving B_{T1} axes are combined with NW–SE or NE–SW orientations of the shear planes and thrust planes. They are related to main imbricate fault zones, bending of the folded sequence along strike, and/or oblique ramping of the layered strata.

Second deformation fabrics

In the steepened to overturned imbricates (Figs. 4 and 14), earlier-formed F_{T1}-folds and S_{T1}-cleavage planes related to the E–W motion of the thrust sheets, as well as the Devonian–Carboniferous sedimentary contact, are cross-cut by conjugate sets of secondary shear planes (C_{T2}). These relate to the steepening of the thrust sheets during progressive E–W shortening. They strike N–S and can further develop as smaller-scaled imbricate faults or high-angle reverse faults. Comparable with the C_{T1}-shear planes, these show a direct relationship between continuing shearing and fault plane developments along conjugate plane sets.

Outside the steepened imbricates, C_{T2}-shear planes, second thrusts and reverse faults could be observed in a few outcrops. Thrusts and high-angle reverse faults are clearly fabrics of the second deformational event where they cut across F_{T1}-folds and/or fold hinges. C_{T2}-shear planes are related to the second-order faults. Like first generation faults, they strike N–S and dip to the east or west. Slickensides, striae and/or bending of the adjacent strata demonstrate E- or W-directed transports along the fault planes. This again suggests that the faults are of a conjugate set supporting a tectonic wedging of the already deformed pile of rocks.

In some outcrops, second-order folds (F_{T2}) around W–E axes occur which overprint S_{T1}- and C_{T1}-planes. Such folds on a scale of several metres could also be observed in the western Precordillera where they refold minor S_{T1}-planes, small-scale F_{T1}-kink folds, as well as fabrics of the Palaeozoic deformation.

Strike-slip shear planes

After the second deformation (D_{T2}), a continuing accommodation of horizontal E–W compression is further shown by conjugate sets of small-scale tear (transfer) faults which cross-cut F_{T1}-folds and C_{T2}-shear planes (Fig. 14). They strike NW–SE or NE–SW and display a sinistral or dextral sense of shear, respectively. It seems realistic to suppose that comparable strike-slip faults observed at the map scale (compare e.g. Baldis & Bordonaro 1984, Fielding & Jordan 1988) are also related to the continuing W–E compression which in some areas led to a bending of the imbricate sequence along strike. Hence, these accommodation tear faults seem to have been responsible for the different amounts of E-directed advance of individual stacks of imbricate sheets during the final movements above the major décollement.

EVOLUTION OF THE MOUNTAIN FRONT

Back thrust zone

Along the eastern boundary of the AP (Fig. 16), the Early Palaeozoic platform sequence does not override the eastern foreland basin sediments of Tertiary age. The Cambro-Ordovician carbonates as well as the Ordovician to possibly Lower Devonian clastics with mélange deposits are unconformably overlain by clastic deposits of Late Carboniferous age. The angular unconformities prove that the eastern border of the AP was inclined towards the east (40–60°), prior to the deposition of the Carboniferous. This clearly contrasts with the situation found in the adjacent parts of the AP to the west where no clear angular unconformity was found at the base of the Carboniferous clastics.

Tertiary deposits lie unconformably on the Carboniferous clastics as well as on the exhumed Cambro-Ordovician carbonates. This suggests that the eastern border of the AP was also inclined towards the east before the Tertiary sedimentation. Tertiary sands, gravels and conglomerates partly fill pockets within the carbonates (Figs. 17a & b) which point to karst phenomena of Late Tertiary age.

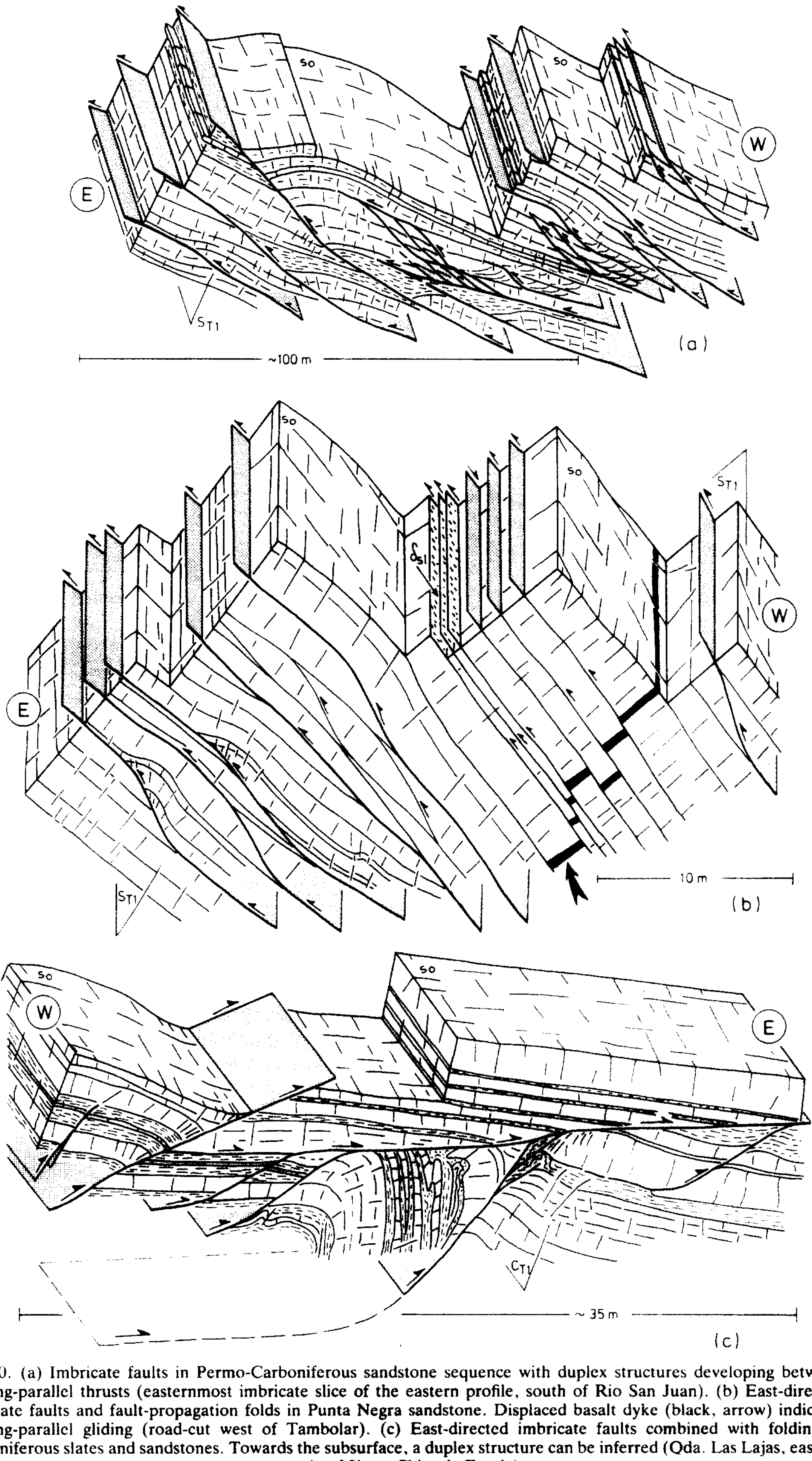

Fig. 10. (a) Imbricate faults in Permo-Carboniferous sandstone sequence with duplex structures developing between bedding-parallel thrusts (easternmost imbricate slice of the eastern profile, south of Rio San Juan). (b) East-directed imbricate faults and fault-propagation folds in Punta Negra sandstone. Displaced basalt dyke (black, arrow) indicates bedding-parallel gliding (road-cut west of Tambolar). (c) East-directed imbricate faults combined with folding in Carboniferous slates and sandstones. Towards the subsurface, a duplex structure can be inferred (Qda. Las Lajas, eastern margin of Sierra Chica de Zonda).

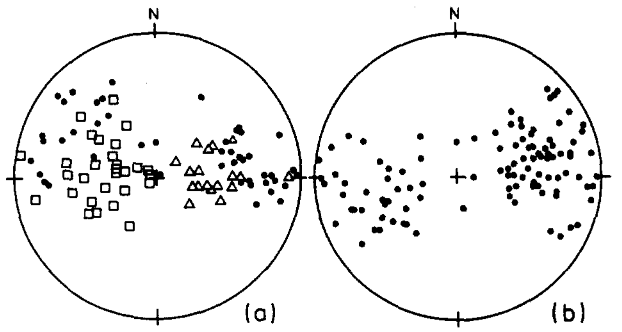

Fig. 11. Lower-hemisphere stereographic projections (equal-area) of D_{T1}-fabrics. (a) Poles of thrusts and back thrusts (dots); squares, slickensides on thrust planes; triangles, slickensides on back thrusts. (b) Poles of C_{T1}-shear planes.

During and after the deposition of Tertiary sediments, the whole eastern margin of the AP was thrust towards the west upon Tertiary basin fillings. At the map scale, one NNE–SSW-striking fault line represents this important back thrust (Fig. 16). However, back thrusting was not restricted to only one thrust plane but was accommodated by a set of W-directed reverse faults forming a *back thrust zone* within the Cambrian–Ordovician carbonates of the Zonda-Villicum range. These use the pre-existing bedding planes of the carbonates or cross-cut them (Figs. 17a & b). The reverse faults also truncate the Tertiary deposits on top of the carbonates, which, on the eastern slope of the carbonate sequence, can be affected by W-directed thrust planes forming back thrust imbricates. These are combined with metre-scale folds (Fig. 17b). Later uplift of the whole back thrust zone led to the formation of coarse talus breccias which are preserved in the Zonda area.

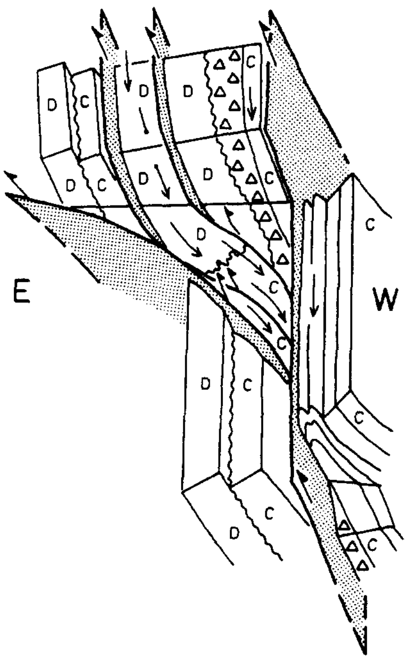

Fig. 12. Three-dimensional sketch of oblique imbrications on a tens of m-scale at the base of Upper Carboniferous–Lower Permian clastics (C) which overlie Devonian sandstones (D; east of Rio Sassito). Sedimentary contacts are shown by wavy lines. Triangles, Upper Carboniferous glazigenic deposits; thin arrows, trend of F_{T1}-axes.

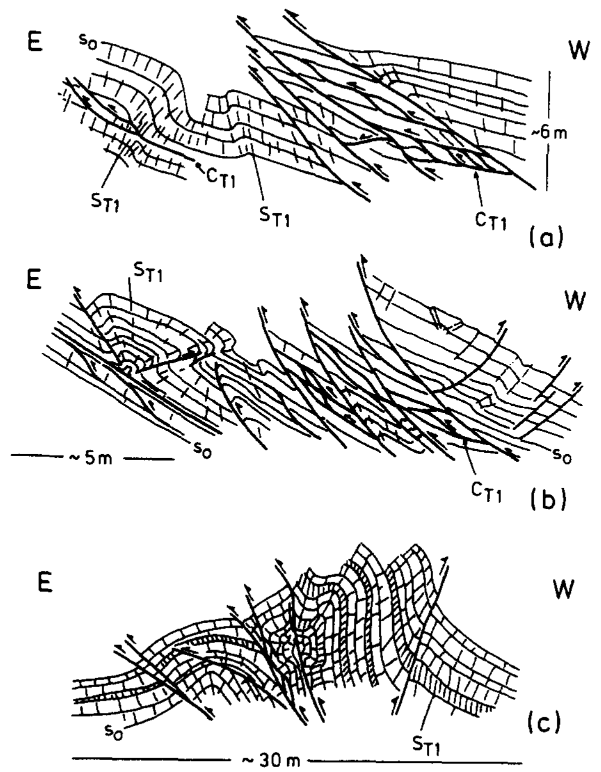

Fig. 13. Tertiary fabrics within Palaeozoic sequences of the Rio San Juan section. (a) East-directed imbricate faults connected by C_{T1}-shear planes cut across a folded sequence in the footwall. Note S_{T1}-cleavage planes related to the folds and drag folds above the western imbricate fault (Devonian sandstones, road cuttings within the easternmost imbricate sheet). (b) Crustal shortening accommodated by a detachment box fold (left) and E-directed imbricates. Note S_{T1}-cleavage planes and small-scaled reverse faults related to the box fold and W-directed back thrusts in the hangingwall of the western imbricate fault (Devonian sandstones, same location as a) (c) East-directed imbricate faults related to F_{T1}-folding. S_{T1}-cleavage planes fan around the folds. In the central part, a F_{T1}-detachment fold is translated along an imbricate fault (Ordovician quartzites and slates, road cutting to the east of Pachaco).

They cover back thrusts and are not affected by reverse faulting.

On a larger scale, *back thrust imbrication* seems to represent the internal style of deformation along the eastern mountain front which can also be inferred from the geological map of the Zonda–Co. Pedernal range (compare Baldis & Bordonaro 1984). The inclination of Palaeozoic strata, directed eastwards prior to the deposition of foreland sediments, suggests that back thrusting was triggered by stratigraphic and structural factors (compare Morley 1986). Hence, the generation of the eastern mountain front is presumably due to the reactivation of an older reverse fault bounding the easternmost inclined strata towards the west.

Subsurface structure

The large-scale anticlinal structure, forming the subsurface to the west of the back thrust zone (Fig. 4), can conventionally be explained by a bending of the carbonate platform together with the underlying Precambrian basement. Taking into account the layered composition of the carbonates, and the competence contrasts with

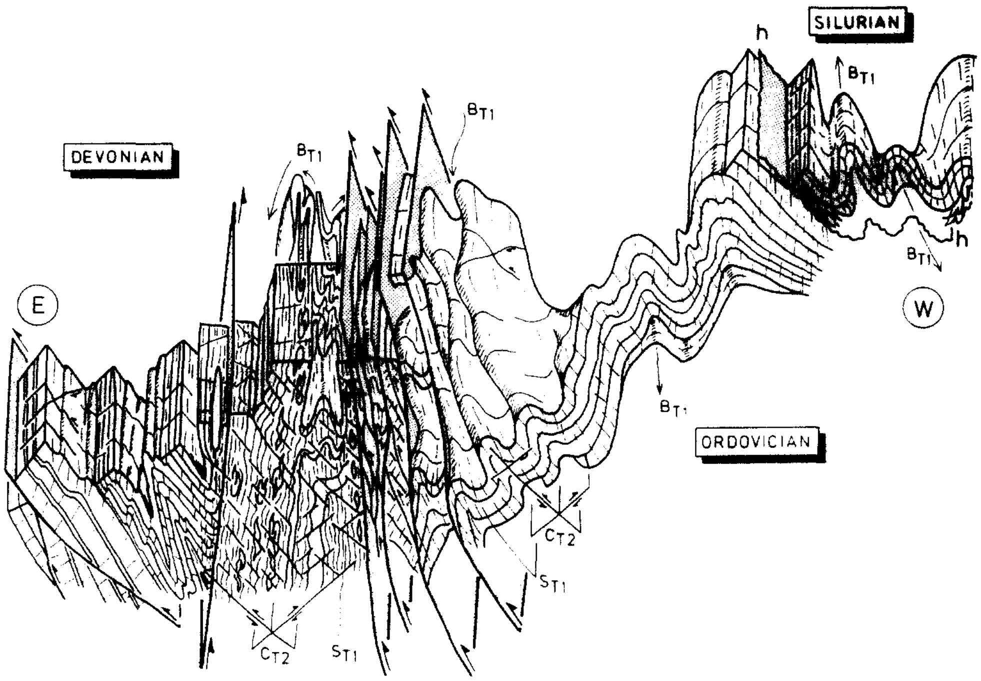

Fig. 14. Schematic diagram of steeply inclined to vertical thrust zone between overriding Ordovician limestone (right) and intensely sheared and folded Devonian sandstones and siltstones (left). F_{T1}-folds of the Ordovician on a scale of several metres, with curved B_{T1}-axes at the base of the thrust sheet, also affect overlying Silurian sandstones and siltstones (h, hiatus at the base of Silurian deposits). Conjugate sets of C_{T2}-shear planes and later-formed (strike-slip) tear faults accommodate continuing lateral compression and cross-cut older fabrics. The intensely sheared zone is a few metres wide at Rio Sasso.

respect to the basement complex rocks, a subsurface duplex structure within the carbonate platform could also explain the anticline. However, this would require postulating a second basal décollement within the deepest parts of the platform sequence which might join the easternmost back thrust zone.

The anticline itself is cross-cut by a back thrust in the Rio Albarracin area (Fig. 4) carrying Devonian sandstones on Tertiary sands. This fault line can be interpreted as an accommodation back thrust at the eastern limb of the anticline with the main detachment horizon to be placed in or at the base of the more incompetent Upper Silurian–Lower Devonian sandstone and siltstone sequence. Back thrusting was presumably triggered by the W-directed push of the main back thrust zone during tectonic wedging along the eastern margin of the AP.

Assuming an additional deep-seated décollement below the duplex structure and above the Precambrian basement means creating an additional component of E–W shortening which must be taken into account when the section will be restored. Due to the lack of any subsurface data, the conventional interpretation of a large-scale bending was preferred in reconstructing the pre-Tertiary configuration.

This general picture of a tectonic wedging at the mountain front can be compared with a similar back thrusting to the north and south of the study area (Huaco: Fielding & Jordan 1988; Mendoza: Sarewitz 1988) and also with structures observed along the eastern front of the Canadian Cordillera (e.g. Charlesworth & Gagnon 1985, Price 1986). The subsurface continuation of the back thrust zone is difficult to assess. At least two possibilities can explain the structure: the back thrust zone could also truncate the unknown Precambrian basement complex (compare Baldis & Chebli 1969, Fielding & Jordan 1988). This could mark the onset of thick-skinned tectonics of the Sierras Pampeanas to the east (Fig. 18a). On the other hand, back thrusting could also be related to a second décollement within the deepest parts of the sedimentary pile (Fig. 18b). This would imply a continuation of this décollement towards the east with the change to a thick-skinned mode of W-directed reverse faulting being placed further to the east. In this case, a 'passive-roof duplex' structure could control the subsurface (cf. Banks & Warburton 1986).

RESTORED SECTIONS

To gain insight into the pre-Tertiary configuration, the sections constructed (Figs. 4 and 8) were restored using the line length method and assuming constant lengths and thicknesses within the thrust sheets before and after deformation. Conventional techniques (e.g. Dahlstrom 1969, Suppe 1980, 1983) were also used to come up with a reasonable picture of the pre-Tertiary situation.

To check the area balancing, the areas of 41 formations in the restored profiles were measured and compared with their equivalents after crustal shortening. The final comparisons gave only minimum differences

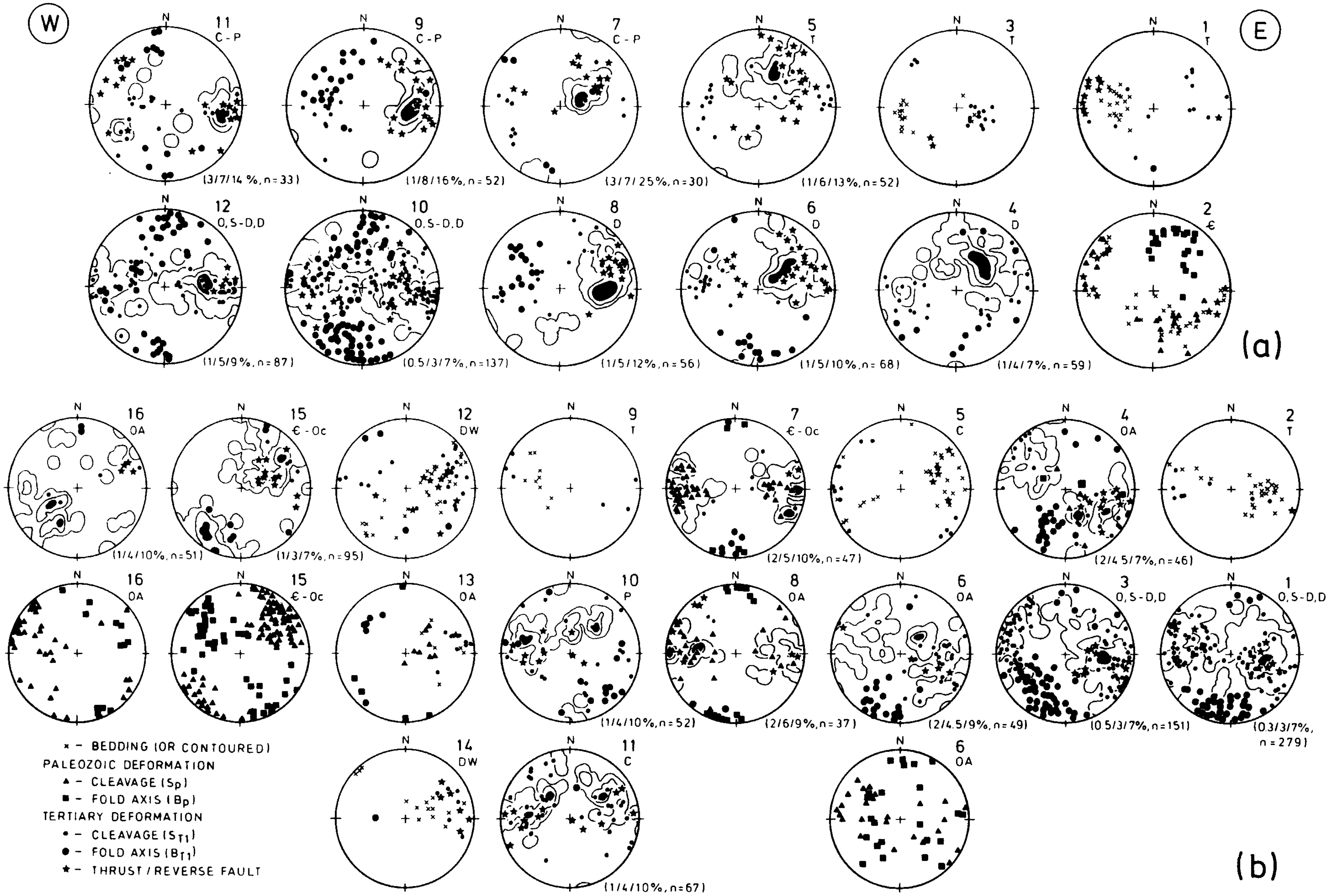

Fig. 15. Lower-hemisphere stereographic projections (equal-area) of Palaeozoic and Tertiary fabrics in the Rio San Juan transect with (a) eastern and (b) western part. Numbers refer to localities shown in Figs. 3 and 7. C, Carboniferous; C-P, Carboniferous–Permian (Paganzo Group); Є, Cambrian (La Laja Formation, Zonda Formation); Є-Oc, Cambrian–Ordovician (Don Polo Formation); D, Middle–Upper Devonian (Punta Negra Formation); DW, Devonian west of km 114; OA, Ordovician (Alcaparrosa Formation and older); O, Ordovician (San Juan Formation); P, Permian; S-D, Silurian–Lower Devonian (Tambolar Formation, Talacasto Formation); T, Tertiary (Miocene–Pliocene).

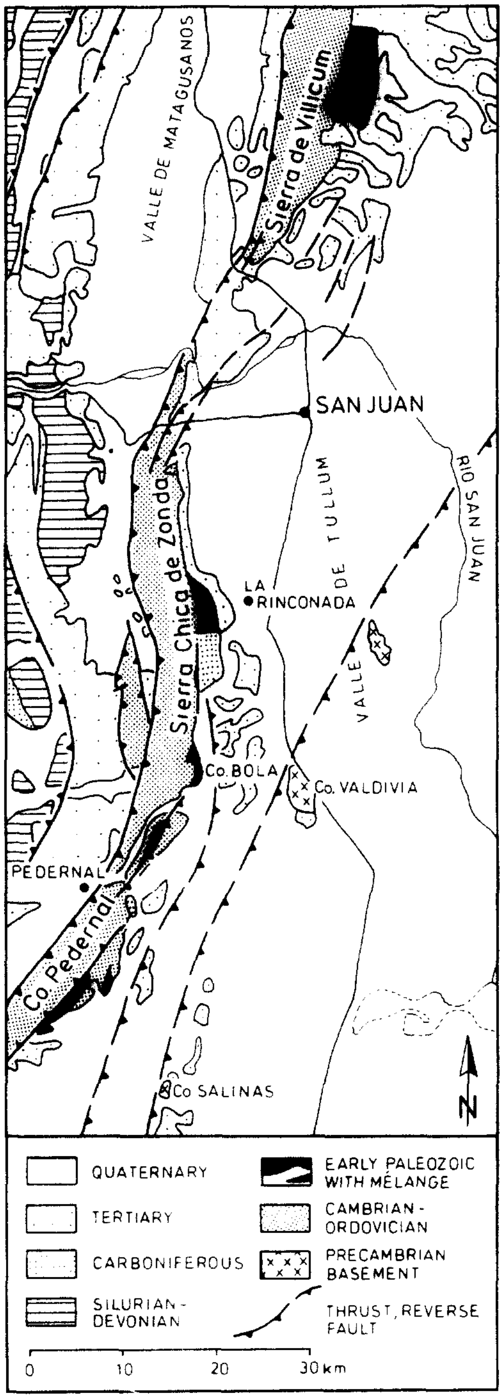

Fig. 16. Sketch map of the eastern margin of the Precordillera with main fault traces and Early Palaeozoic mélange-bearing deposits. Compiled and adapted after Baldis & Bordonaro (1984), Peralta (1984), Zambrano (unpublished map), and own investigations.

which are mostly related to the unknown subsurface geometry of the western slope area (Fig. 8).

To get preliminary restorations, several assumptions had to be made, as follows.

(1) Thrusting was accompanied by flexural- and interstratal-slip. Penetrative strains are small and thus can be ignored. Microstructures, as well as shapes of fossil relics, suggest that there was no penetrative strain leading to a significant compaction of the sedimentary pile during folding and thrusting.

(2) The amounts of layer-parallel shortening within the imbricates, accomplished by folding on a m-scale, duplex generation and bedding-parallel slip, must have been neglected. As no indications for a stretching perpendicular to the sections were found, bulk plane strain conditions with λ_2 being oriented perpendicular to the sections were assumed.

(3) Difficulties arose where the thicknesses of stratigraphic units could not be precisely determined. This occurred in particular where the important Upper Silurian–Lower Devonian horizon crops out with different thicknesses. Like in the Devonian Punta Negra Formation their deformation is mostly controlled by flexural-slip folding and bedding-parallel gliding. Furthermore, Baldis (1975) has shown that the Talacasto Formation exhibits different stratigraphic thicknesses throughout the AP. Hence, only estimates of minimum thicknesses could be used. For the carbonate platform deposits, a 2500 m thickness (Baldis & Bordonaro 1984) was used.

As no subsurface information was available, the preliminary reconstructions had to rely on surface data (dip of thrust planes and strata, cut-off angles and thicknesses of different units) which were used to construct the profiles and restored sections. Tectonic displacements can be best estimated if the base of the Tertiary deposits is taken as a horizontal reference line. This neglects a slope dipping gently eastwards during Tertiary sedimentation.

Earlier workers (e.g. Baldis & Chebli 1969, Ortiz & Zambrano 1981) have shown that a décollement exists within the Ordovician carbonate sequence which is also indicated by the lack of Precambrian basement rocks within the thrust belt. Taking also into account only minimum amounts of displacement along thrusts, this all leads to the minimum estimate of depth of the décollement above the Precambrian basement (Figs. 4 and 8). The depth can be compared with those given by Baldis & Chebli (1969) and Ortiz & Zambrano (1981).

However, in the area southeast of Jachal, which is more than 100 km to the north of the study area, Allmendinger *et al.* (1990) have shown that the depth of the décollement is ~15 km. Up to now, no indications allow such a depth of the décollement to be postulated in the profiles presented here, although a deeper position within the western parts of the AP cannot be ruled out.

When both sections studied across the AP are combined (Fig. 19), the resulting E–W transect will give a length of about 77 km. If this is compared with the 165 km length of the restored pre-Tertiary section an estimated W–E shortening of more than 50% results. If a deeper position of the décollement is postulated, this would significantly enlarge the amount of crustal shortening.

From the restored eastern section it is clear that the easternmost pile of Palaeozoic rocks (Fig. 4) represents a more or less flat-lying platform sequence covering the basement complex rocks. Along the eastern rim of the AP, it is truncated by a fault line dipping eastwards which was reactivated as a back thrust during crustal shortening. In the eastern area, the main décollement

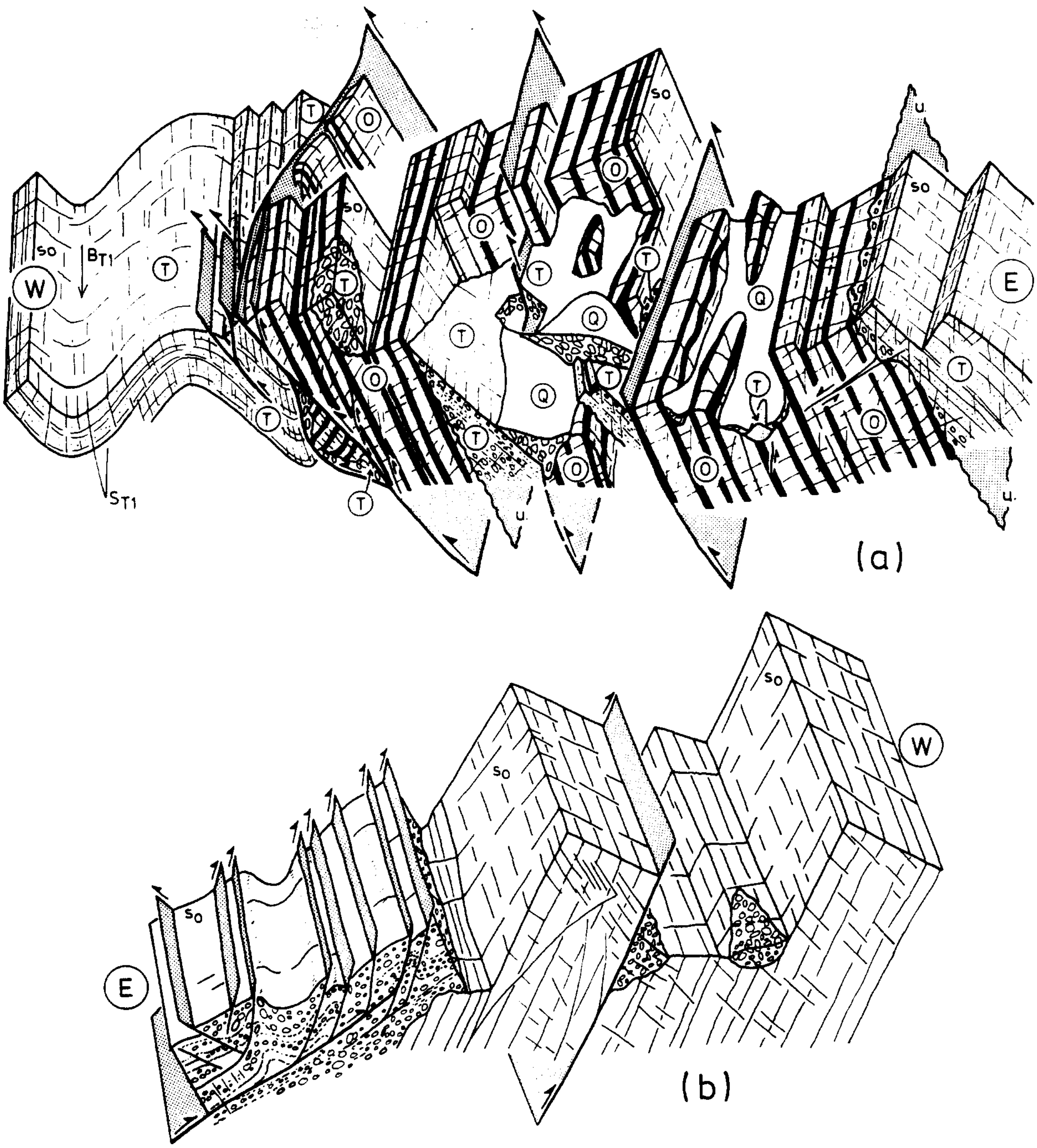

Fig. 17. (a) Block diagram showing back thrust zone at the southernmost border of the Sierra de Villicum. Back thrusts displace Cambro-Ordovician carbonates (O) as wells as Tertiary sands and conglomerates (T) (Q, Quaternary cover, u., unconformity, length of schematic sketch ≈300 m; for further explanations see text). (b) West-directed back thrusts truncate Cambrian carbonates (right) with Tertiary breccias preserved in pockets as well as conglomerates and sands on top of the carbonates dipping eastwards (length of schematic sketch ≈50 m; entry to Qda. Las Lajas, eastern margin of the Sierra Chica de Zonda).

lies within the more incompetent rocks of the Silurian to Lower Devonian unit. From west to east, it cuts up-sequence with the upper parts of the San Juan limestone containing the décollement in the western areas (Fig. 4). It is possible that the eastern imbricates at their base contain thin limestone layers. To the north and south of the transect, they could also carry parts of the uppermost Ordovician limestones which would indicate an oblique ramping along strike. Whether a second décollement exists in the basal parts of the Cambro-Ordovician carbonate platform sequence also depends on the sub-surface interpretation of the eastern mountain front discussed previously.

Above the main décollement, imbricate faults cut up-section leading to the 'piggy back' mode of thrusting. This style of crustal shortening implies that (parts of the) Late Tertiary deposits on top of the imbricates are also passively carried towards the eastern foreland. Such explanation also accounts for the Tertiary basins along the western rim of the AP. Studies of Beer *et al.* (1990) have shown that the Tertiary sediments of the Iglesia Basin record the discontinuous motion of the thrust

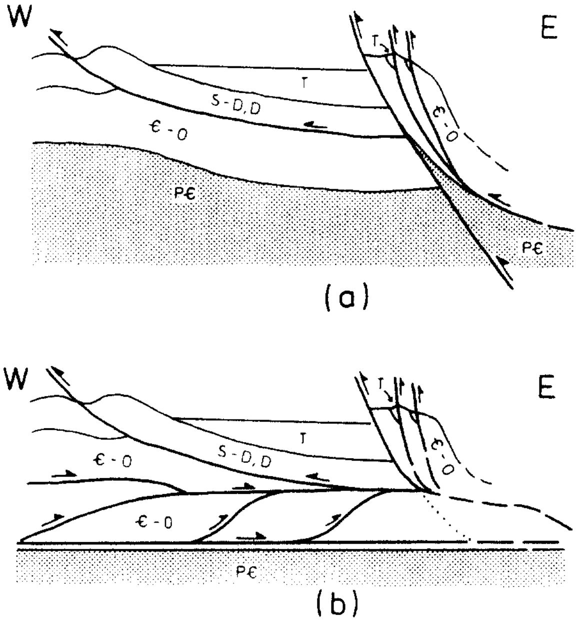

Fig. 18. Cartoons to illustrate the possible evolution of the eastern mountain front. (a) Back thrusting is due to the onset of a thick-skinned mode of W-directed reverse faulting with the main fault cutting through the Precambrian Basement. (b) Back thrust imbricates generate on top of an E-directed duplex structure within the Cambrian–Ordovician carbonate sequence. Towards the east, the main back thrust either cuts down-sequence (dashed line) or joins the basal décollement within the basal parts of the carbonate sequence (dotted line). €-O, Cambrian–Ordovician carbonate sequence; P€, Precambrian Basement; S-D,D, Silurian–Devonian sequence; T, Tertiary sediments.

sheet towards the east. Like the Iglesia Basin, the deposits of the Rio de Los Patos Tertiary (Fig. 7) are also affected by later movements which display the continuing motion of the already covered thrust sheets at the western margin of the Precordillera.

From the preliminary reconstructions (Figs. 4 and 8), the Precambrian Basement complex is shown to extend as a more or less undeformed autochthonous slab to the area west of Pachaco and may floor the imbricated Palaeozoic strata. However, additional thrusts parallel to the main décollement probably occur within the Precambrian complex.

The transition between the eastern carbonate platform and the western Cambrian to Ordovician clastic sequence is expected to occur west from Pachaco. Without subsurface information these areas were difficult to interpret. Hence, the western parts of this restored section are less valuable due to the lack of a reference horizon. The restoration (Fig. 8) contains a lot of interpretations with only minimum amounts of displacement along the thrust planes taken into account. However, the profile shows the general geometries and allows one to postulate a transitional slope towards a western basin area. Up to now, the precise geometry of the platform margin remains uncertain.

Between the Silurian to Devonian clastic sequence and the Cambro-Ordovician carbonates, the Alcaparrosa Formation (Ordovician) and underlying strata mark the transition towards the basin. The slope itself is characterized by Cambrian–Ordovician carbonates with mélange deposits (Los Sombreros Formation) which are exposed to the south of the research area. The profiles and restored sections (Fig. 8) suggest that the formation of the slope area was controlled by extension faults dipping westwards. These form the western platform boundary and might also displace the Precambrian Basement complex. During crustal shortening they were partly reactivated as imbricate faults. Towards the west, the Cambro-Ordovician block of the Sierra del Tontal contains the basin sediments (Don Polo Formation).

The reconstruction further suggests that thrust faults in the western parts of the AP dip towards the west as well as the east (Fig. 8). The fact can be interpreted in terms of contemporaneously developing conjugate sets of thrust faults: Tertiary compression led to tectonic wedging, with the Sierra del Tontal area uplifted by a main transport on the basal décollement(s) and by imbricate faults propagating eastwards. This was combined with the initiation of back thrusts along the western margin of the Sierra del Tontal and in the westernmost parts of the section. Back thrusting was the response of foreland-directed reverse faulting which was combined with the uplift of huge blocks of basin sediments. Ramping along the former continental slope might have enhanced or initiated the wedging process.

TIMING OF THRUST TECTONICS

The ages of individual thrusts could not be assessed. However, the pattern of imbricate faults verging eastwards, together with the orientation of the flooring décollement, suggest that thrusting initiated in the western areas and then gradually propagated towards the east. Again, this is comparable with the situation observed in the Canadian Cordillera (see Brown *et al.* 1986).

As there are no Cretaceous sediments preserved in the area studied, an onset of crustal shortening during Early Tertiary and/or Cretaceous times cannot be excluded. However, basalt dykes in the Cerro Morado anticline to the north of the Sierra de Villicum and their radiometric dating (Cuerda *et al.* 1981, 1984) suggest that Upper Cretaceous times were dominated rather by crustal extension than by crustal shortening.

There exist only a few data to constrain the timing of thrust movements in the region. These are mainly derived from Tertiary clastics and volcanics (Leveratto 1976, Contreras 1981) which in eastern regions are affected by thrust tectonics. As the clastics received pebbles derived from the Frontal Cordillera in the west (e.g. rhyolites) it seems reasonable to suggest that a more or less peneplained surface may have existed before the onset of thrusting in the AP.

Sedimentologic and magnetostratigraphic research at several localities in the AP, combined with fission track dating of volcanic intercalations (e.g. Tabbutt *et al.* 1987, Beer *et al.* 1990, Jordan *et al.* 1990), have shown that this landscape existed up to 10 Ma before present. In the eastern parts of the study area, crustal extension

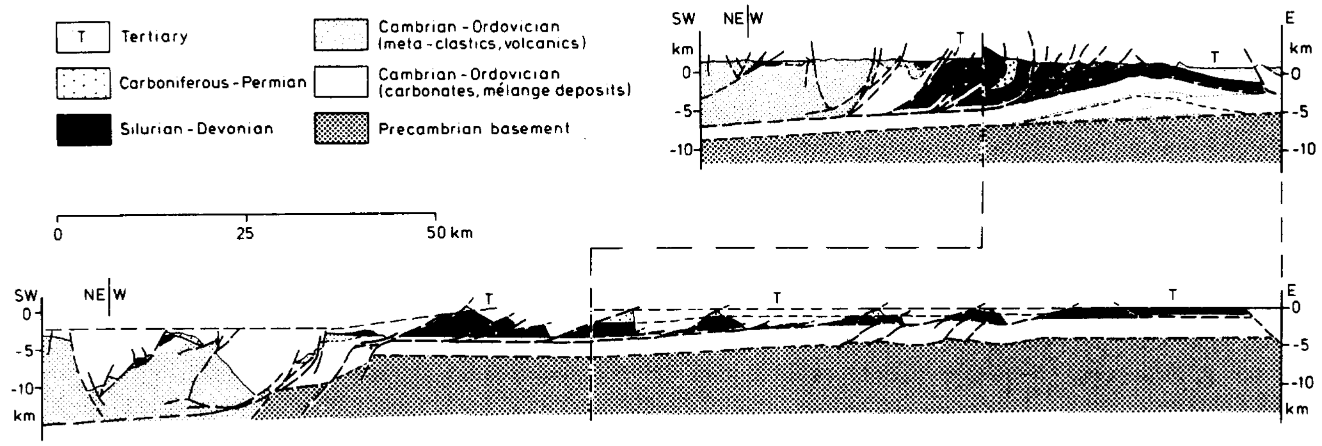

Fig. 19. Composite cross-section across the Precordillera (top) and restored section (bottom). Dashed line indicates offset between eastern and western profiles studied (for further explanations see text).

with the generation of andesitic to dacitic volcanics (Leveratto 1976: K–Ar, amphibole, 47 ± 10 Ma; plagioclase, 16 ± 2.9 Ma) pre-dates the onset of crustal shortening. Fission track dating of pyroclastic rocks along the eastern and northeastern parts of the AP has shown that the volcanic activity spanned a 10–4 Ma interval (Johnsson *et al.* 1984, Johnson *et al.* 1986, Tabbutt *et al.* 1987, Jordan *et al.* 1990).

The first break in sedimentary conditions took place at about 10 Ma which marks the onset of thrust tectonics in the western AP (Beer & Jordan 1989). From the similarity of the Tertiary deposits in the western areas, containing also rhyolite pebbles, it is highly probable that the Sierra del Tontal range did not exist as a major N–S-trending barrier before 10 Ma. However, Damanti *et al.* (1988) and Beer *et al.* (1990) have shown that the deformation was diachronous along strike with an onset in the northern parts of the AP at about 16 Ma.

Within the still growing intramontane depressions and the eastern foreland basin, clasts from local source areas occur at 8.7 Ma (Beer & Jordan 1989). They mark the continuous thrusting and uplift in the central AP, and pebbles supplied by Ordovician and older carbonates suggest that the carbonate platform was partly exhumed. According to Jordan *et al.* (1985) thrusting migrated eastwards and might have affected the eastern AP after 2.3 Ma.

Along the eastern margin of the AP as well as the western parts of the Sierras Pampeanas basement, E–W compression occurred during Pliocene up to recent times. This is expressed by high-angle reverse faults dipping eastwards which displace Late Tertiary and Quaternary deposits (e.g. Uliarte & De Gianni 1982, Martos & Bastias 1985). Reverse fault lines also occur along the western margin of the uplifted Sierras Pampeanas basement blocks to the east of the AP (compare Fielding & Jordan 1988). Studies on earthquake focal mechanisms and levelling data have revealed the existence of eastwards and/or westwards dipping fault planes within the basement which account for the recent crustal shortening and uplift (e.g. Kadinsky-Cade *et al.* 1985, Triep 1987, Langer & Bollinger 1988).

PRE-TERTIARY EVOLUTION

Extension faulting

In the eastern section of the E–W transect, no angular unconformities between the Permo-Carboniferous (Paganzo Group) and the Devonian sequences (Punta Negra Formation) were found in the field. This suggests that no important post-Devonian movements have affected this part of the AP. However, the restored section displays the existence of half-graben structures which were presumably bounded by westwards dipping extension faults along their eastern margins. These grabens must have actually occurred, as Tertiary sediments on both sides either cover Devonian or Permo-Carboniferous deposits. At both graben margins, the latter are exposed with different thicknesses (Fig. 4).

The extension is interpreted as accommodated by westwards dipping faults which flatten and might become listric in deeper parts of the section. It is a reasonable interpretation that they use the more incompetent Silurian to Lower Devonian sequence as a bedding-parallel detachment horizon. Within deeper crustal regions, extension was presumably accommodated by steeply inclined normal faults truncating the carbonate platform as well as the Precambrian Basement (Fig. 4). As there are no indications for present normal faults to be preserved in this part of the AP, these might have been reactivated by the later-formed imbricate faults. Examples from other orogens (e.g. Price & Todd 1988, Bless *et al.* 1989, Casagrande *et al.* 1989) suggest this to be a realistic assumption.

The formation of half-graben structures, triggered by extension faults dipping westwards, suggests an uplift along the eastern margin of the AP. Their eastern counterparts can be found at the eastern margin of the Sierra Chica de Zonda (Qda. Las Lajas). There, extension faults dipping eastwards used the steeply inclined bedding planes of the Cambro-Ordovician carbonates which are displaced against Carboniferous clastics (Fig. 6a). Coarse conglomerate layers thin out towards the east, and they cover locally smaller-scale synsedimentary extension faults. At one place, the conglomerates and sandstones contain angular m-scale blocks of carbonates. Within one sandstone layer, isoclinal slump folds were found. This synsedimentary extension faulting is confirmed by sedimentological research of Bercowski (1987) and was accompanied by a sediment transport directed northeastwards (Bercowski 1985).

The reactivation of extension faults postulated above could be observed in the Qda. Las Lajas, at the eastern rim of the Sierra Chica de Zonda. There, an extension fault was reactivated as a steeply inclined reverse fault with a sandstone sequence having been thrust upon the former normal fault. Additional small-scaled reverse faults and back thrusts mark the hangingwall of the overprinted extension fault.

In the km 114 area of the western AP (Figs. 7 and 8) differently oriented faults, and the age relationships between the adjacent rock sequences, demonstrate that earlier-formed extension faults may have operated. Inverted Permian sandstones which override Carboniferous conglomerates as well as Devonian sandstones, overthrusting Ordovician sequences, cannot be related to a continuous stratigraphic sequence prior to crustal shortening. They indicate the generation of syn- to post-Carboniferous graben structures which were triggered by synsedimentary normal faults. This is also shown by Permian sediments which unconformably overlie Carboniferous strata (Figs. 6b and 9) and in turn again are unconformably covered by Triassic sandstones.

Extension faulting presumably initiated during Late to post-Carboniferous times and led to the formation of locally subsiding depressions and graben structures. These were filled with locally derived material but pebbles supplied by glacial transport also occur. Turbiditic deposits of Late Palaeozoic age, described by Lopez Gamundi (1986) from the western margin of the AP (Calingasta–Uspallata area), can be possibly related to these tectonic movements. Normal faulting continued probably during Permian and Triassic times. However, areas of crustal mobility seem to have been shifted towards the west. There, unconformities at the bases of Permian and Triassic strata, and also the restored section (Fig. 8), give evidence for extension faulting initiating during the Late Carboniferous but continuing up to post-Triassic times.

To the south of the research area, extension faulting is described from the Mendoza area (Strelkov & Alvarez 1984) where horst-and-graben structures are generated during Triassic times. Crustal extension during Late Palaeozoic to Triassic times is also indicated by widespread volcanic activity (e.g. Thompson & Mitchell 1972, Salfity & Gorustovich 1983, Strelkov & Alvarez 1984). Basalt dykes in the Devonian Punta Negra Formation (west of Tambolar, Fig. 10b) might represent parts of these eruptions. Measurements of the N–S-striking dykes, and their rotation back into the pre-Tertiary position, suggest that W–E extension has taken place which can be related to the overall extension since Late Carboniferous times.

Pre-Carboniferous deformation

Folding and cleavage. In the Sierra del Tontal, the Cambro-Ordovician clastics of the Don Polo Formation, as well as the Ordovician sequence, are affected by a pre-Carboniferous deformation (D_P) expressed by folding (F_P) verging westwards which is combined with a penetrative slaty cleavage (S_P). Cross-bedding, load casts and graded bedding on a cm-scale indicate upright layering of the strata before the deformation occurred.

The outcrop pattern in the western profile (Fig. 8) shows that amplitudes and wavelengths of F_P-folds vary from a m-scale to km-scale (Fig. 20a). F_P-fold axes strike N–S to NW–SE (Fig. 15) but E–W axes also occur. The reasons for the different axes orientations near the western margin of the AP are unclear. F_P-folding in the km 114 area and in the westernmost parts of the AP is also expressed by folds of several metres, verging towards the east or west.

S_P-cleavage planes are closely spaced and are parallel to the axial planes of F_P-folds. Cleavage refraction can be seen where interbedded sandy and shaly layers occur. Within some folds, S_P-planes are of a conjugate set intersecting under low angles. In only a few outcrops, a more or less E–W-striking stretching lineation (L_P) could be observed which is mostly recorded by aligned sericite and muscovite. S_P-cleavage planes also cut across Ordovician pillow lavas and dykes of basic volcanics (Fig. 20b). The latter may have represented channels for the upwards migrating lava flows and seem to be older than the basalt dykes cutting across the Devonian sequences (Fig. 10b).

Field evidence and the restored section suggest that there is an increase in F_P-folding from east to west. To the east of the Sierra del Tontal only a few small-scale folds with different axes orientations and some shear planes are related to a pre-Carboniferous deformation. In the central parts of the AP no clear D_P-fabrics could be observed up to now. There, all the fabrics studied can be related to the Tertiary thrust tectonics.

However, in the easternmost parts of the AP (Zonda–Villicum range; Figs. 4 and 16), the Early Palaeozoic deposits are folded around N–S- to NE–SW-striking axes. Flexural-slip F_P-folds verging to the west or to the east are combined with isoclinal fold types. West-directed transport is indicated by large-scale duplex structures within the Ordovician San Juan Formation which were found at the eastern margin of the Sierra de Villicum (Fig. 21). As far as can be seen, the western limit of folding and thrusting coincides with the Tertiary back thrust which seems to mark an important boundary between the easternmost and central parts of the AP.

Metamorphism. F_P-folding and S_P-cleavage formation in the western parts of the AP were combined with a slight metamorphic overprint. It led to synkinematic growth of sericite and chlorite. Quartz clasts exhibit ductile deformation accommodated by pressure solution and by incipient internal strain revealed by undulatory extinction, kinking and the formation of a few subgrains.

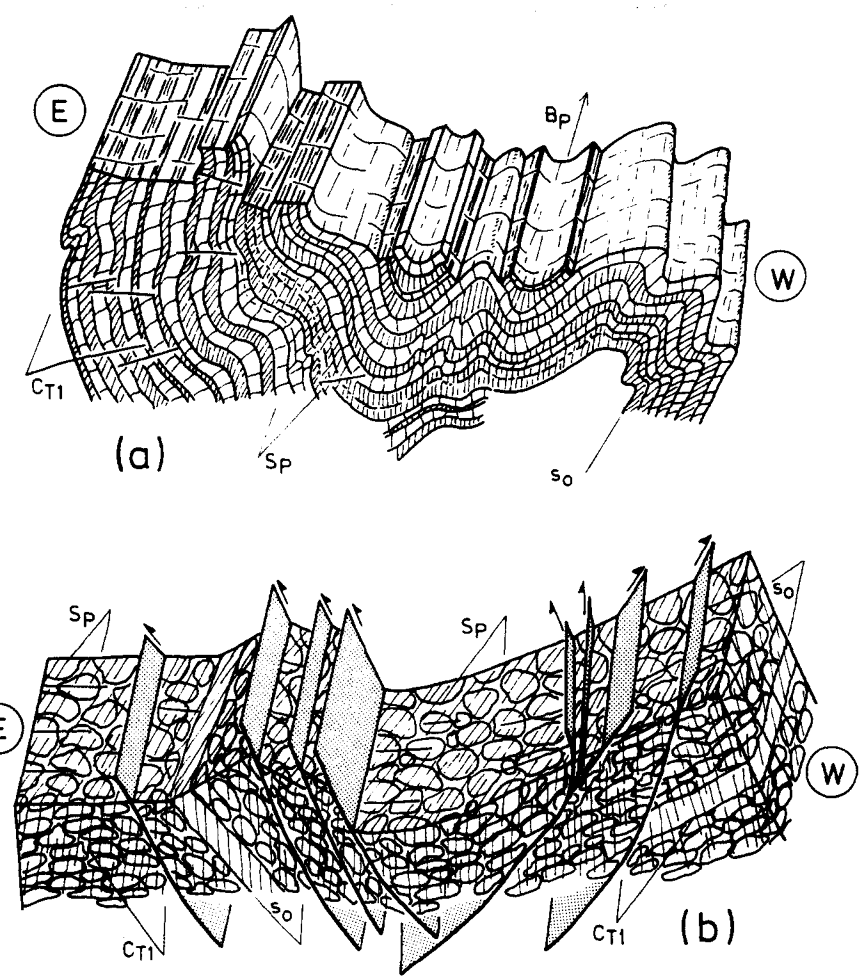

Fig. 20. (a) Large-scale F_P-folds verging westwards in (?) Cambro-Ordovician meta-clastics. S_P-cleavage planes represent the dominant tectonic fabric (length of generalized sketch ≈2 km; western part of Sierra del Tontal, south of Rio San Juan). (b) Composite schematic sketch of Ordovician pillow lavas which are cross-cut by S_P-cleavage planes and conjugate sets of Tertiary reverse faults dipping east- and westwards. The latter are accompanied by C_{T1}-shear planes (road cuttings between kms 127 and 128.3 near Calingasta, valley of Rio de Los Patos).

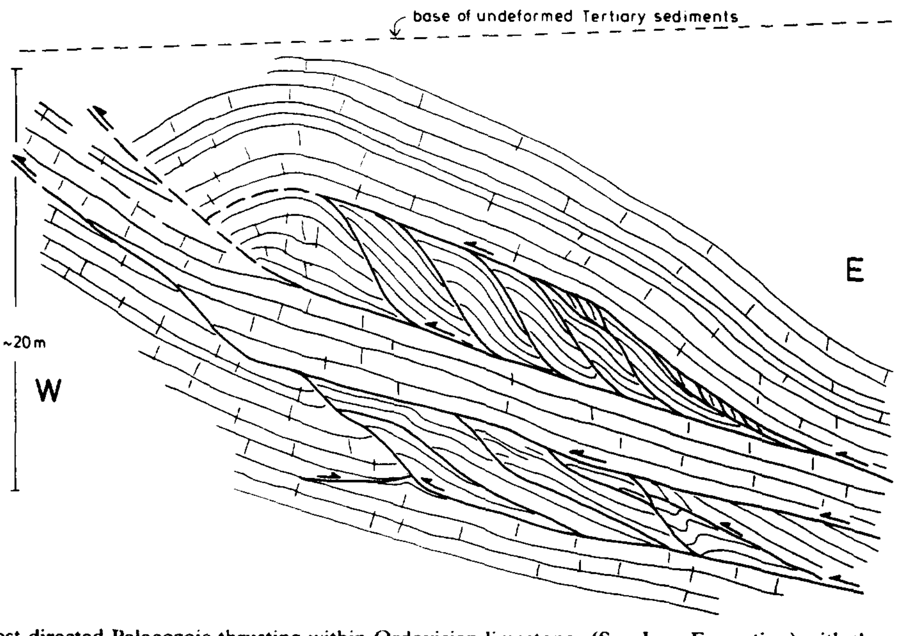

Fig. 21. West-directed Palaeozoic thrusting within Ordovician limestones (San Juan Formation) with the generation of duplex structures. The thrust zone is covered by undeformed Tertiary sediments (valley south of Qda. Don Braulio, eastern margin of the Sierra de Villicum).

Within a few samples, dynamically recrystallized quartz grains could be detected at quartz–quartz boundaries. They suggest that the metamorphic grade might have reached lower greenschist facies conditions in the western AP. Up to now, no indication was found to postulate a metamorphic overprint in the central and eastern areas of the AP.

Timing of deformation and metamorphism. As Silurian slates in the Calingasta area (western rim of the AP) are affected by the D_P-deformation and metamorphism, both events seem to have affected the western AP during post-Silurian times. Whether Devonian sediments are also involved remains unclear. Clastic sediments in the km 114 area and to the west of it, which I interpret as Devonian, did not give evidence for S_P-cleavage formation, F_P-folding and metamorphism comparable with the D_P-deformation and metamorphism in the adjacent Ordovician sequence. However, Cuerda *et al.* (1988) have shown that a Late Devonian folding occurred northwest of Mendoza. It affects Ordovician and Lower Devonian strata which are separated by an unconformity.

K–Ar whole rock data of schists from the western part of the study area yielded Devonian ages (365 and 365 ± 18 Ma; Gonzalez-Bonorino & Aguirre 1970, Cucchi 1971). Three dolerites of the Calingasta area gave ages of 350 ± 15, 352 ± 15 and 399 ± 15 Ma (Linares 1978) which are consistent with K–Ar whole-rock data from two phyllites and one phyllonite of the Uspallata area (350 ± 17, 403 and 403 ± 20 Ma: Gonzalez-Bonorino & Aguirre 1970, Cucchi 1971). These few data point to a thermal activity which affected at least the western and southwestern parts of the AP during Silurian–Devonian times. It should be pointed out that the Rb–Sr dating of metamorphic rocks from the southern AP indicates a regional metamorphism with a minimum age of about 500 Ma (Caminos *et al.* 1982).

REGIONAL IMPLICATIONS

The restored transect across the AP (Fig. 19) displays geometric features which can be compared with the pre-deformational geometries of the Rocky Mountains (compare Bally *et al.* 1966, Price 1981). Between an eastern platform plus underlying basement rocks and the western basin sequence there existed a remarkable transition. Comparable developments along the mountain fronts are also evident and were already pointed out by Jordan & Allmendinger (1986) and Fielding & Jordan (1988).

Another important point emerges from the restored E–W transect. If the base of the Tertiary is taken as a horizontal reference line, then the pre-Tertiary deposits in the eastern and western parts of the AP exhibit a large-scale synclinal bending. As rhyolite pebbles were transported on a Cenozoic peneplain prior to 10 Ma, the bending, uplift and erosion must have occurred earlier. Hence, it seems reasonable to suggest that the bending of the lithosphere was triggered by the subducting Nazca Plate in the west during pre- to early Miocene times.

From the restored section, it is clear that the eastern platform area towards the western basin is bounded by a transitional slope containing sedimentary mélange deposits. It seems reasonable to assume that the northern and southern continuations of the slope can be seen in the areas west of Jachal and in the Los Sombreros area (Sierra del Tontal), respectively. From the area to the west of Jachal, huge blocks of carbonates within a slate matrix are already described by Heim (1952).

Several slump folds in the Cambro-Ordovician and Ordovician clastics of the study area indicate a westerly sedimentary transport direction. Within the Devonian Punta Negra Formation slump folds increase in abundance towards the west, and the sediments become more flysch-like in character. The folds suggest a transport towards the west, which is confirmed by palaeocurrents studied by Gonzalez Bonorino (1975). Thus, a basin region might have existed up to Upper Devonian times in the western AP. There was no evidence found to postulate a deformational event combined with metamorphism which might have interrupted the sedimentary infill.

The transect studied reveals no evidence to support a 'Proto-Precordillera' in the central and western parts of the AP, or a mountain range during Devonian and Carboniferous times. All the evidence found suggests that a Devonian basin formation was followed by block faulting during the Carboniferous (compare also Gonzalez Bonorino 1976, 1990).

Slope deposits occur also along the eastern margin of the AP (Fig. 16) where they constitute the upper parts of the Rinconada Formation and equivalents (Fig. 2). These contain huge allochthonous blocks of carbonates and conglomerates, and, according to Amos & Fernandez (1977) and Peralta & Uliarte (1985), I interpret this mélange to be of sedimentary origin. Up to now it is unclear whether the sedimentary transport was directed towards the east or west.

The transition between the eastern margin of the AP and the eastern metamorphic basement of the Sierras Pampeanas during Early Palaeozoic times creates a problem. K–Ar dating in the western parts of the metamorphic complex, to the east of the AP, has shown some data which fall into the Precambrian to Silurian time periods (Gonzalez-Bonorino & Aguirre 1970, Linares & Aparicio 1976, Toubes Spinelli 1983, Cuerda *et al.* 1984). The data reflect a complex metamorphic history of the basement complex which strongly contrasts with the non-metamorphic character of the Cambrian and younger platform sequence of the AP to the west.

As no fabrics were found in the study area to postulate a terrane boundary within the AP, a presumed boundary could be somewhere to the east of the AP. One interpretation might be to relate the mélange deposits along the Zonda–Villicum range to such a terrane boundary (compare Ramos *et al.* 1986). However, up to now no fabric studies exist which could give evidence for important strike-slip faults triggering movement of the AP during Early Palaeozoic times.

In contrast, the interpretation of a seismic profile by Cominguez & Ramos (1990) has shown W-directed imbricates within the basement complex to the east of the AP. The structures were interpreted to be of pre-Andean age and related to the collision between the Sierras Pampeanas and the AP (Cominguez & Ramos 1990). It seems likely to postulate such W–E convergence between the AP and the Sierras Pampeanas Basement complex which could also explain the folding and thrusting exposed in the Zonda–Villicum range (eastern margin of the AP, Fig. 21). The later-formed back thrust along the western margin of the range could represent an older reactivated reverse fault indicating the western limit of the collision zone.

The post-Silurian compression in the AP seems to follow an orthogonal trend with respect to the present N–S strike of the mountain chain. It seems most reasonable to suggest that the W-verging folds were related to Early Palaeozoic subduction along the margin of the South American part of Gondwana. The restored transect shows that the location of the trench area must be shifted further to the west.

CONCLUSIONS

The transect studied across the Argentine Precordillera allows us to distinguish between several tectonic events which can be summarized as follows.

(1) Thin-skinned high-level thrusting and folding above at least one basal décollement occurred during Late Tertiary times and was triggered by a 'piggy back' mode of imbrication. E–W crustal shortening of at least 50% was accommodated also by back thrusting which represents the most important structural feature of tectonic wedging along the eastern margin of the Precordillera.

(2) Crustal extension, shown by normal faults, suggests that the easternmost part of the study area represents a mobile crustal segment during Late Carboniferous times. In the central and western Precordillera, intense crustal mobility, expressed by block faulting, seems to have continued up to post-Triassic times.

(3) A large-scale folding event, combined with cleavage formation and a slight metamorphic overprint, affected the western Precordilleran rock sequences during post-Silurian times. The deformation seems to be related to the Palaeozoic subduction process which affected the Palaeo-Pacific margin of Gondwana. According to the sections restored this subduction zone has to be placed to the west of the Precordillera.

(4) The restored transect shows that the central Precordillera is composed of a flat-lying Early Palaeozoic platform. A slope area, containing also mélange deposits, indicates the transition towards a western basin.

The clear contrast between the Early Palaeozoic strata of the eastern Precordillera and the metamorphic basement of the Sierras Pampeanas to the east, which underwent a complex tectono-metamorphic history, makes it necessary to postulate an important pre-Carboniferous boundary. Since no evidence was found to postulate such a boundary within the Precordillera itself, it could be expressed by the mélange deposits which occur along the eastern margin of the Precordillera. Imbricate faults directed westwards within the Sierras Pampeanas basement, as well as folding and thrusting within the eastern Precordillera, account for a W-directed compression between both blocks during Palaeozoic times. Due to the lack of any additional structural evidence and fabric analyses, the nature and location of this boundary remain uncertain.

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