

## Neogene structures overprinting Palaeozoic thrust systems in the Andean Precordillera at 30°S latitude

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**Abstract:** Field studies along a 30°S latitude transect of the Precordillera in NW Argentina indicate that Neogene to recent deformation caused high-angle faulting that uplifted and breached a Palaeozoic east-verging thrust stack. Palaeozoic structures crop out in the higher linear ranges, and intramontane Neogene basins occur in the intervening valleys. The Palaeozoic rocks include three tectonic units with contrasting structural styles and differences in stratigraphy. The Western Allochthon includes clastic Ordovician rocks metamorphosed to lower greenschist facies and folded by large-scale asymmetric, east-verging folds with a well-developed axial planar cleavage. This unit overthrusts a Siluro-Devonian flysch-type succession of the Central Imbricate thrust system and associated fault propagation folds in which the thrusts merge into a basal thrust beneath Ordovician carbonates. Middle to Upper Carboniferous sediments unconformably overlie structures of this imbricate system. In the Frontal Unit minor thrust faults are interpreted to explain the low-angle unconformity within Palaeozoic rocks. Neogene deformation causes only a minor overprint of the Palaeozoic structure, and large-scale folding in the Frontal Unit appears to be mostly of Neogene age. The new data indicate that Neogene intracontinental shortening may be smaller than previously proposed, providing new perspectives on the present orogenic architecture along this Andean section.

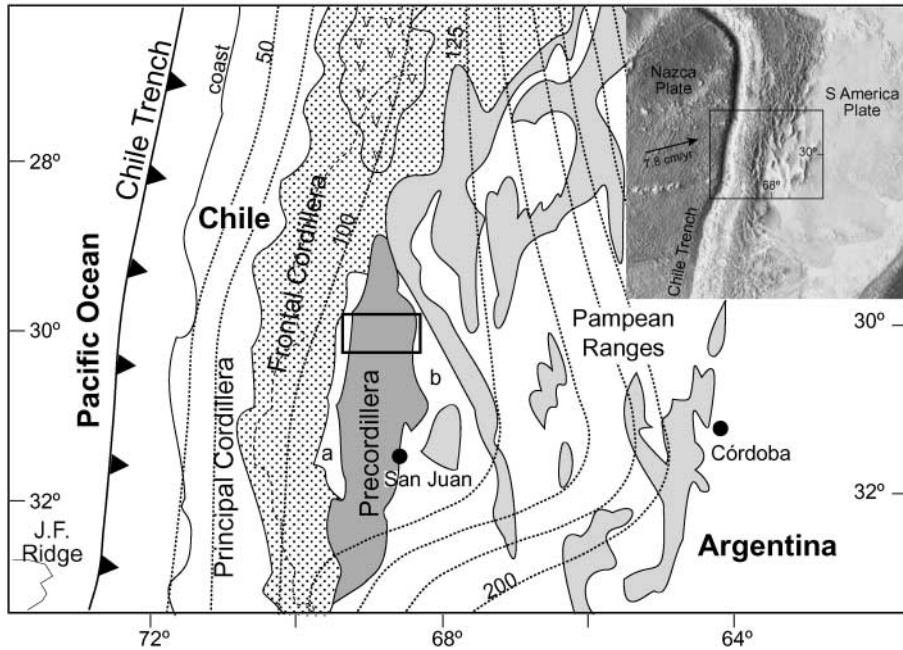
The segment of the Andean orogen between 29 and 33°S latitude is divided into several geological provinces that form north–south-trending belts (Fig. 1; Ramos 1988). This segment records geological processes interpreted to be associated with the evolution of an active continental margin since the Early Palaeozoic (Ramos 1988; Rapela *et al.* 1998). In the foothills, the Precordillera of NW Argentina has played a key role in a number of tectonic interpretations, with implications for the whole orogenic section (Ramos 1988; Allmendinger *et al.* 1990; Dalziel 1997; Ramos *et al.* 2002). However, fundamental data for the understanding of the structural evolution of the Precordillera and the deformation processes involved in the construction of this part of the orogen remain controversial or insufficiently constrained. For example, the existence of pre-Andean deformation within the Palaeozoic sedimentary strata in the Precordillera has been described (e.g. Furque 1979; von Gosen 1997), yet there is no general agreement on the number of Palaeozoic deformation events, their timing or their distribution. Consequently, contrasting interpretations of the Palaeozoic tectonic framework remain, because aspects such as the structural geometries, vergence and kinematics are not well known. In addition, a few studies have integrated structural data for both Andean and pre-Andean structures. Discriminating between Andean and pre-Andean structures and their interference is fundamental for deciphering the structural architecture that resulted from different deformation events, and to establish the tectonic evolution of the Precordillera.

Along the deeply incised valley of the Jáchal River, which runs perpendicular to the strike of the Andean foothills, an almost continuous, 50 km long section of the Precordillera is very well exposed (Fig. 2). This paper presents a field-based

structural study of the area, aided by 1:50 000 scale aerial photographs, Thematic Mapper satellite images and mostly 1:250 000 scale geological maps of the Argentinian Geological Survey (SEGEMAR) (Furque 1979; Furque *et al.* 1998; Cardo 2006). The study focused on a structural analysis of both the Andean and pre-Andean deformations to establish their geometries and to discriminate the characteristics of each deformation event. The integrated geological cross-section along the Jáchal River area provides a new view of the structure of the region, and new data for interpreting the tectonic evolution along this section of the Andean external zone.

### Geological framework

The Precordillera of Argentina forms the external zone of the Andes between 29 and 33°S (Ramos 1988). It overlies a subhorizontal portion of the subducted Nazca plate (Cahill & Isacks 1992), and has lacked major magmatism since *c.* 10 Ma (Kay *et al.* 1988). The Precordillera forms an elongated 400 km long by 80 km wide belt of mostly Palaeozoic rocks that reaches maximum elevations of 4000 m (Fig. 1). It is bounded to the west and east by active Cenozoic basins. The Iglesia–Calingasta Basin covers the structural boundary with the Cordillera Frontal in the west, and in the east the Bermejo Basin is part of a larger foreland basin that is disrupted by large Proterozoic basement uplifts (Sierras Pampeanas). Most previous structural studies of the Precordillera focused on two east–west sections along cross-cutting river valleys that provide the best access and exposure (Allmendinger *et al.* 1990; von Gosen 1992, 1997). The northernmost of these valleys is that of the Jáchal River near 30°S.



**Fig. 1.** Map of western South America showing the main provinces of the Andes between 29 and 33°S latitude, above a segment of shallow angle of subduction of the Nazca plate (dashed lines are contours of Wadati–Benioff zone from Cahill & Isacks (1992)). The Principal Cordillera in Chile includes north–south-trending low ranges and basins; the Frontal Cordillera includes the areas of highest topography, the Precordillera forms the foothills; the Sierras Pampeanas are ridges of basement that pop up within the foreland basin sediments. The large active basins that bound the Precordillera to the west and east are marked, the Iglesia–Calingasta Basin (a) and the Bermejo Basin (b). The box represents the study area and location of maps in Figures 2 and 3. The inset shows a portion of the Central and Southern Andes next to the Nazca plate that subducts slightly obliquely (75° azimuth) along the Chile Trench at 7.8 cm a<sup>-1</sup> (DeMets *et al.* 1994).

This study focuses on this northern section of the Precordillera, between the towns of Rodeo and Huaco (Fig. 2).

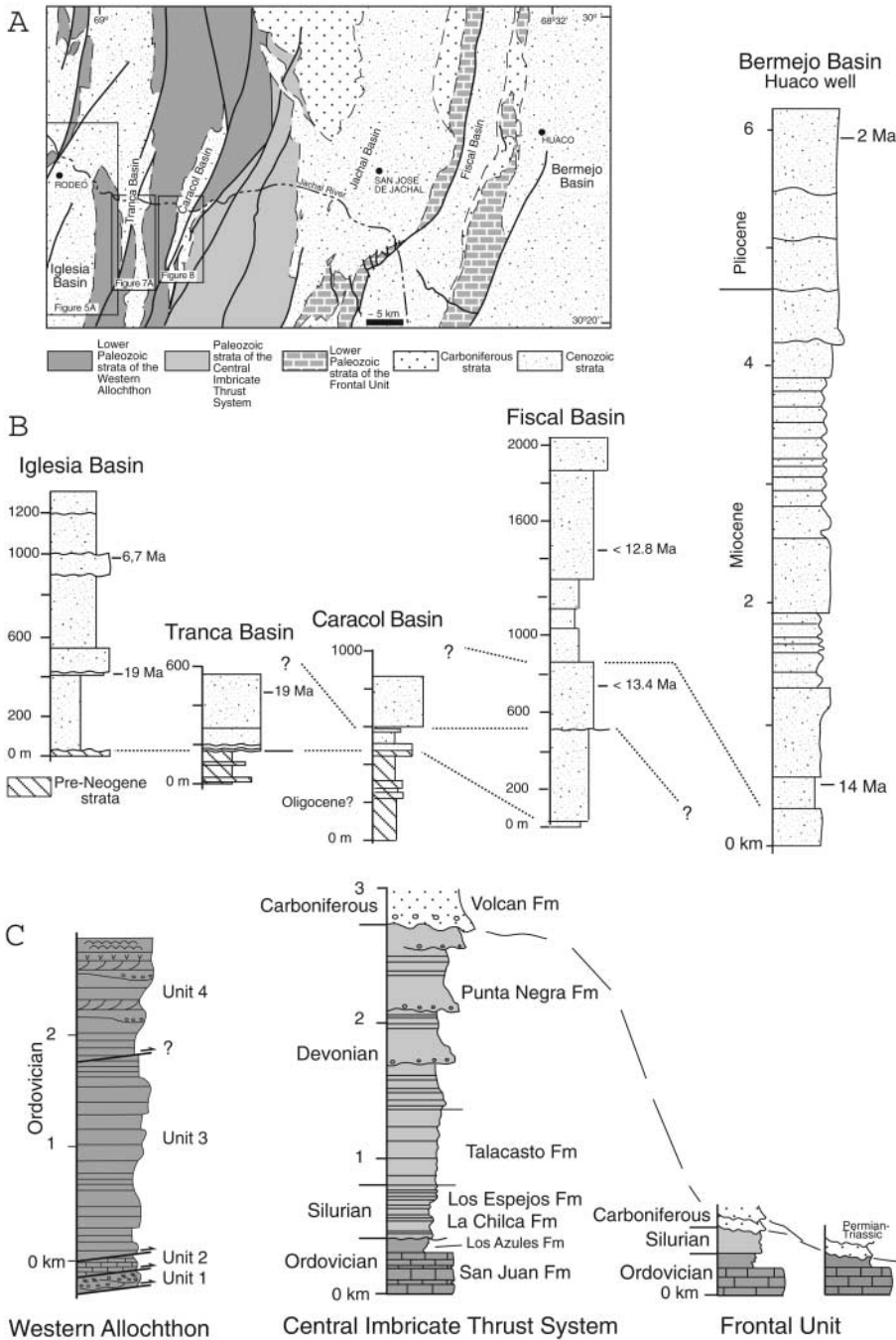
Previous studies in this region interpreted the Andean structure as a set of Neogene, emergent thrust faults that carry previously deformed Palaeozoic and younger cover rocks (Allmendinger *et al.* 1990; Jordan *et al.* 1993; von Gosen 1997). Neogene thrust-related shortening and syntectonic intramontane basins have developed during the last 18 Ma, simultaneous with the process of slab shallowing (Jordan *et al.* 1993; Ramos *et al.* 2002). The Neogene thrusts have been interpreted to cut upwards from a deep décollement at  $\geq 15$  km and to have caused 95 km of shortening (Allmendinger *et al.* 1990). Large thrust faults underwent simultaneous motion, and local out-of-sequence thrusting has been documented (Jordan *et al.* 1993). The syntectonic basins are filled by continental-facies Neogene sediments with large lateral lithological and thickness variations (Fig. 2). For instance, the Iglesia Basin near Rodeo contains up to 3.5 km of dominantly fine-grained lacustrine and fluvial, upper Miocene to Pliocene sediments (Beer *et al.* 1990). The intramontane Tranca Basin contains <600 m of dominantly red and brown conglomerates (Jordan *et al.* 1993). The Bermejo foreland basin contains >5000 m of Tertiary continental sediment in a well drilled near Huaco (Zapata & Allmendinger 1996a). The Tertiary sediments of the Bermejo foreland basin are deformed in the Huaco area, east of the area considered here, by hinterland-verging structures related to west-directed basement involved thrust faults (Zapata & Allmendinger 1996a). These structures started to form by 2.7 Ma and are still active (Zapata & Allmendinger 1996a).

The oldest rocks within the Jáchal River area of the Precordillera are Lower Palaeozoic sediments that are unconformably overlain in the central and eastern regions by Carboniferous sediments (Furque 1979). Locally, Permian continental conglomerates (Furque *et al.* 1998) and red beds of possible Triassic age are found (Zapata & Allmendinger 1996a). The Lower Palaeozoic stratigraphy varies greatly from east to west (Fig. 2). In the west, a large thickness of siliciclastic and volcanic rocks is attributed to the Ordovician, including an outcrop of pillow basalts of 2 km width beneath the contact with Iglesia Basin sediments, and a unit with large calcareous olistoliths and mass-

flow deposits bounds the Ordovician sequences in the east (Furque 1979; Astini *et al.* 1995; von Gosen 1997). In the central part, a large thickness of Siluro-Devonian siliciclastic sediments is underlain by thinner Lower Ordovician carbonates of the San Juan Formation (Furque *et al.* 1998). Although the boundary between the Silurian and Devonian is not well established, the Devonian series includes a thin-bedded unit with mostly siltstones in the lower part and a thicker-bedded unit with sandstones and conglomerates in the upper part (Fig. 2). Furque *et al.* (1998) described a low-angle unconformity beneath Silurian sediments that overlie the San Juan Formation, which is of Early Ordovician age, or a younger thin unit of Ordovician clastic sediments. The deformed Siluro-Devonian sediments are unconformably overlain by Carboniferous strata of the Volcan Formation, which crops out to the north of San José de Jáchal (Furque 1979). In the easternmost part of the Jáchal River area, the oldest rocks are the Ordovician carbonates of the San Juan Formation, which are overlain by a thin veneer of Siluro-Devonian rocks (Furque 1979). At one locality thin Upper Cambrian limestones were found concordantly beneath the San Juan Formation (Furque *et al.* 1998). Palaeozoic deformation in the Jáchal River area has been studied by von Gosen (1997), who described different fold types and vergences that were interpreted to have been influenced by a former escarpment related to a normal fault within the Early Palaeozoic basin. West of the escarpment, Ordovician basin and slope sediments were folded and underwent low greenschist-facies metamorphism. To the east, the Early Palaeozoic carbonate platform underwent west-verging folding without a clear metamorphic overprint (von Gosen 1997). Von Gosen proposed a Devonian to pre-Late Carboniferous age for the structures in the east, and argued for a possibly older age (Late Silurian) for the structures in the west.

### Structure of the Jáchal River area

Structural analysis of the Jáchal River area is focused along a 50 km wide mapped transect from the eastern margin of the Iglesia Basin in the west to the easternmost outcrop of Palaeozoic rocks near Huaco (Fig. 3). Along this transect, a NNE–



**Fig. 2.** (a) Geological sketch map of the Jáchal River area showing the distribution of Palaeozoic and Cenozoic strata and locations of detailed maps shown in other figures. Palaeozoic outcrops appear in the high topographic areas forming ridges and Cenozoic sediments occupy the low-lying areas. (b) Simplified stratigraphy of several Cenozoic basins, redrafted from Beer *et al.* (1990) and Jordan *et al.* (1993, 2001). (c) The stratigraphy for the Palaeozoic strata is presented in three columns corresponding to the Palaeozoic thrust units. In the Western Allochthon the synthetic column is modified from Astini *et al.* (1995) and represents the four lithotectonic units described in the text. Units 1 and 2 correspond to the mélangé; Units 3 and 4 correspond to the eastern and western parts of the allochthon. The stratigraphy for the Central Imbricate thrust system is based on Furque *et al.* (1998), and that for the Frontal Unit is based on Zapata & Allmendinger (1996a); and Furque *et al.* (1998) (see text for description of lithologies).

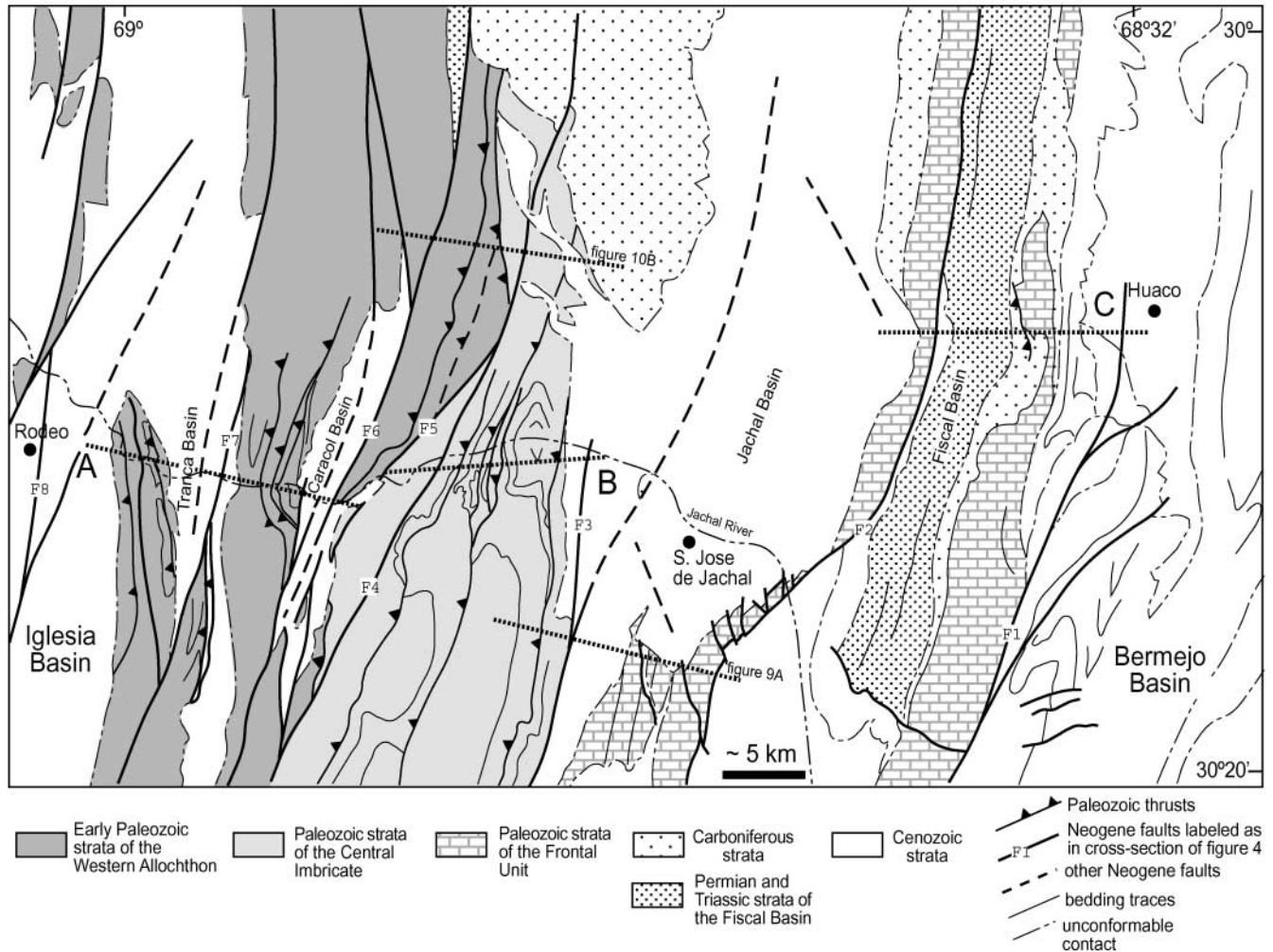
SSW-trending fault system appears to be responsible for the spatial distribution of the Palaeozoic and Cenozoic outcrops, which produces a topographic pattern that consists of north-south-trending ridges and depressions. The ridges include the outcrops of deformed Palaeozoic strata and the depressions are occupied by Cenozoic sediments within fault-related basins. Large, active, Quaternary alluvial fans appear along most of the ridge slopes and cover previous sediments and structures in topographic lows. In particular, interpreted Neogene fault traces are covered for distances of tens of kilometres in the northern part of the Jáchal Basin (Fig. 3). The Quaternary alluvial fan stratigraphy is exposed in sections of tens of metres along the sides of the Jáchal River as a result of the progressive incision of the river.

The composite cross-section along the Jáchal River area illustrates the geometries of the Palaeozoic and Neogene to recent structures (Fig. 4). The Palaeozoic deformation resulted in an east-verging thrust stack, and the Neogene to recent deformation resulted in a high-angle fault system breaching through and uplifting the previous Palaeozoic thrust stack, and forming related intramontane basins.

#### Neogene structures and associated basins

Along the Jáchal River section of the Precordillera, the sedimentary basins that developed between the outcrops of previously deformed Palaeozoic rocks appear to be related to high-angle faults that form a linked fault system in map view (Fig. 3). The





**Fig. 3.** Geological map of a 50 km wide strip of Precordillera in the Jáchal River area. (Note the Jáchal River running along the central part.) The main Neogene faults are shown by bold lines, dashed when covered by Quaternary alluvial fans (faults are marked F1–F8 for correlation with the cross-section in Fig. 4). Palaeozoic thrusts are represented by fine lines. Segments A, B and C indicate the location of geological cross-sections (Fig. 4). The map is based on field mapping and 1:250 000 geological maps of Rodeo (Cardo 2006) and San José de Jáchal (Furque *et al.* 1998). Permian and Triassic rocks of the Fiscal Basin are not differentiated.

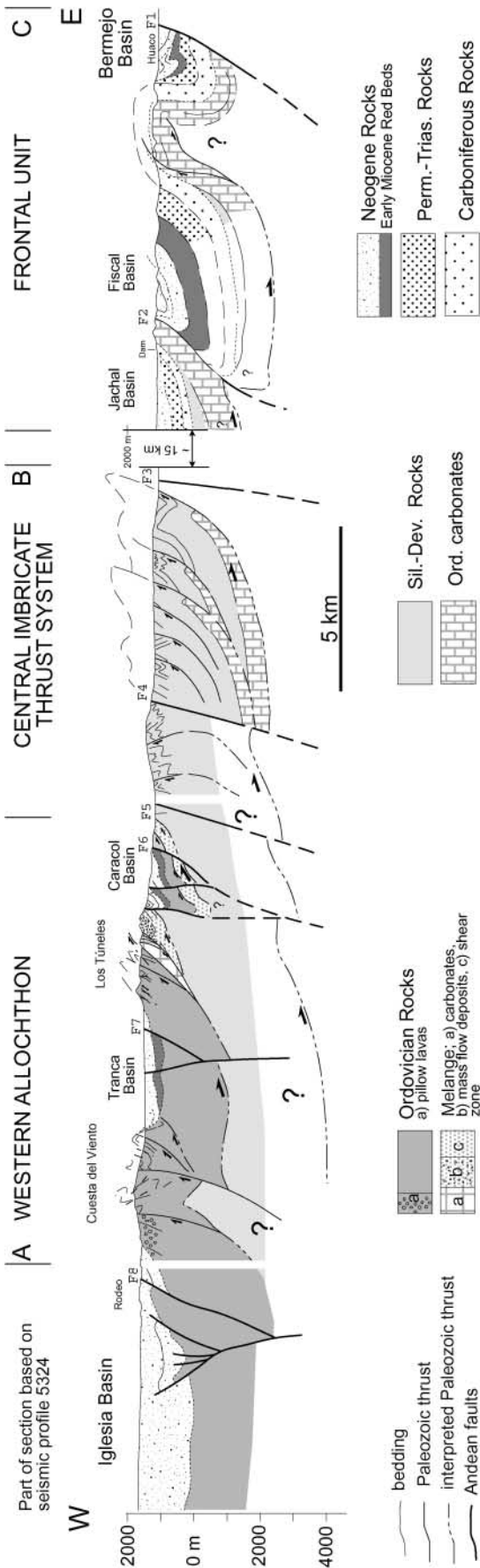
linkage is less apparent in the eastern part of the map. The basins include Neogene continental-facies sediments that were deposited synchronous with fault activity from 18 Ma (Jordan *et al.* 1993). In some basins, older sediments of Permian to Tertiary age have been described (Furque 1979; Jordan *et al.* 1993). The basins differ in dimensions, sedimentary thickness and facies, and in the distribution of unconformities within the Neogene sequences. Correlations of sedimentary packages and major unconformities from one basin to another are hampered by geographical isolation.

The Neogene fault system comprises several fault sets (Fig. 3). The dominant set consists of NNE-striking high-angle faults that in most cases are east-directed thrusts (Fig. 4), although north-south-striking reverse faults and less well-developed NW-striking faults are also present. The major faults typically display fault gouges that can be several metres wide. Reliable kinematic indicators are rarely developed within the fault gouges, especially when the faults cut the soft and unconsolidated Neogene sediments. Where the Neogene faults affect the Palaeozoic rocks,

slickensides with gentle SW plunges ( $<40^\circ$ ), indicative of oblique displacement, have been found. Structures at a scale of metres to tens of metres, such as folds and faults, accompany the major faults, and deform the sedimentary sequences within the basins. These minor structures allow interpretations of fault kinematics based on geometric relationships between linked fault planes and fault-related folds (see below).

In the following sections, the Neogene structures and the relationships between the major faults, associated minor structures and syntectonic sediments are described in detail, taking examples from several basins.

*Structures in the Iglesia Basin.* The Iglesia Basin constitutes the northern part of the *c.* 150 km long Iglesia–Calingasta Basin that separates the Precordillera from the Cordillera Frontal (Figs 1 and 2a). Previous studies in this northern area proposed that the basin includes a Neogene sequence up to 3.5 km thick, and interpreted the basin as a piggyback basin that developed during the eastward advance of Precordillera thrusts (Beer *et al.* 1990;



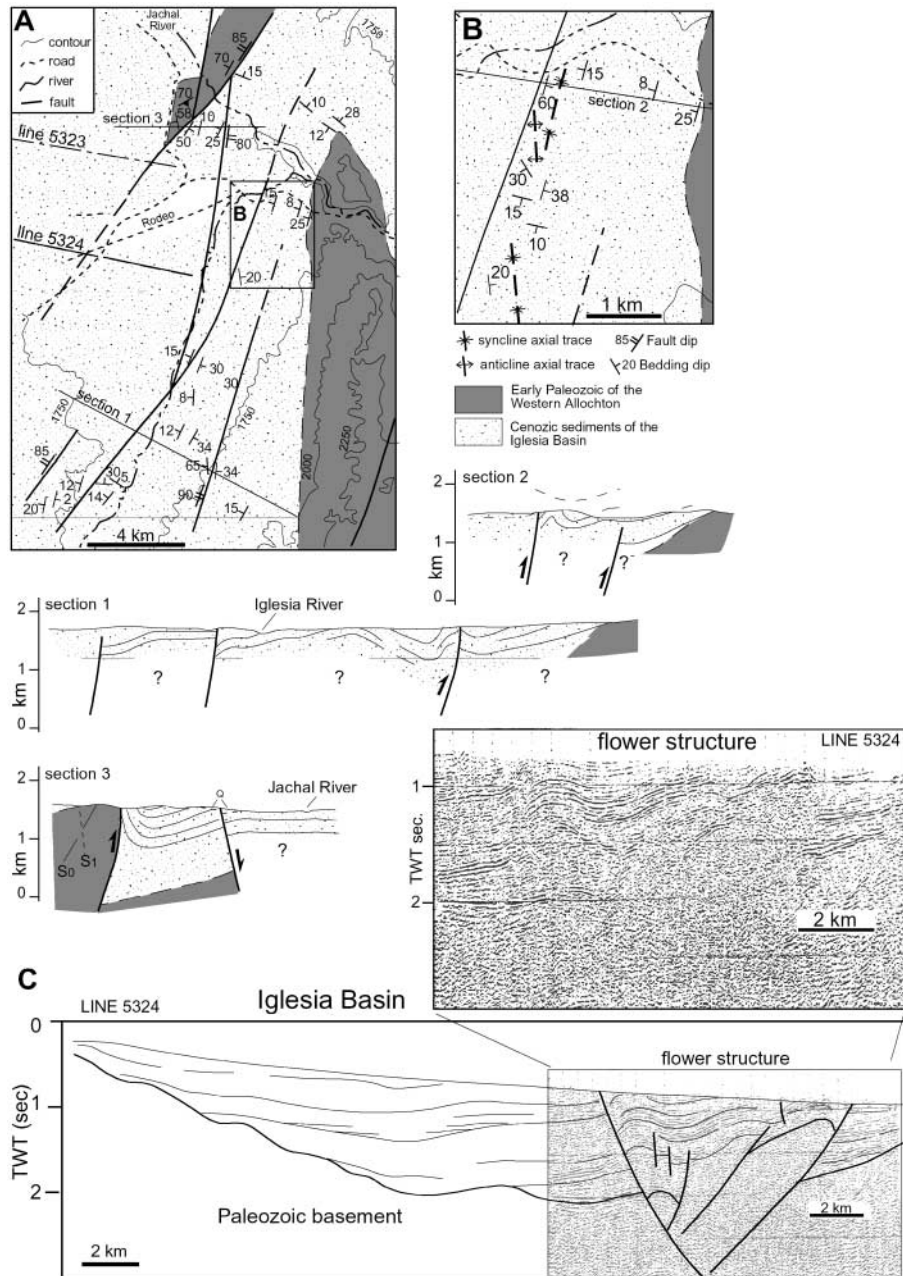
Jordan *et al.* 1993). The Iglesia River deformation zone, which affects the eastern part of the Iglesia Basin, corresponds to the northward prolongation of the El Tigre Fault as shown in Argentinian geological maps (Cardo 2006). The El Tigre Fault is a *c.* 120 km long active strike-slip fault within the Iglesia–Calingasta Basin. Recent deformation along this fault has been dated by right-lateral displacements along alluvial fan surfaces of 20–700 ka age some 70 km south of Rodeo, where slip rates of  $1 \text{ mm a}^{-1}$  have been calculated (Siame *et al.* 1997).

The geometric characteristics of Neogene structures within the Iglesia Basin are well exposed in a NNE-trending deformation zone of several kilometres width following the valley of the Iglesia River (Fig. 5). Along the deformation zone Miocene to Pliocene sediments of the basin fill, together with some isolated outcrops of Palaeozoic basement, are exposed (Fig. 5a). Major faults are steeply dipping at the surface, with fault planes dipping  $80^\circ$  or more, and may show reverse or normal vertical throws (see sections 1, 2 and 3 in Fig. 5). Changes in dip direction along strike are also found. Sediments commonly form steep monoclines near the fault planes, and away from the faults they form either wide zones of subhorizontal bedding or very open folds of varied geometries and dimensions. Progressive unconformities are developed within the fault-related monoclines and, locally, at the contact with Palaeozoic basement rocks. These geometries indicate that sedimentation was synchronous with fault activity. Folds are non-cylindrical folds on a scale of tens of metres, and have abrupt lateral terminations (Fig. 5b). In outcrop, minor, metre-scale thrusts and associated fault-propagation folds show east and west vergence.

The seismic reflection sections across the Iglesia Basin provide a 2D image of the basin structure. The sedimentary fill is very well imaged above the sharp top basement reflection (Figs 5c and 6). The sediments are progressively younger as they onlap the basement towards the west. A zone of deformation in the east includes east- and west-directed faults with an apparent reverse throw and some minor faults with apparent normal throw. In Figure 6, syntectonic sediments above fault A thicken towards the crest of the fault-related anticline. These geometries of double vergence and distribution of sedimentation apparently unrelated (in a 2D view) to the faulting are commonly related to strike-slip fault systems (Sylvester 1988). On the basis of the outcrop data and the seismic sections we therefore interpret the large-scale architecture of the deformation zone within this part of the Iglesia Basin as a positive flower structure with Miocene to Pliocene sedimentation synchronous with fault activity (Figs 5c and 6).

**Fig. 4.** Composite geological cross-section of the Precordillera in the Jáchal River area. The section is based on detailed structural data taken along the outcrops near the road cut parallel to the Jáchal River (segments A and B) and the road to Huaco (segment C). Minor inconsistencies in dimensions between the cross-section and map of segment B are due to differences in projection between the satellite image used for drawing the map and the 1:100 000 scale topographic maps used for drawing the cross-section. The interpretation of seismic profile 5324 across the Iglesia Basin is added in the west (the location of this profile is shown in Fig. 5). The section shows a Palaeozoic east-vergent thrust stack breached by high-angle Neogene faults that have associated basins (faults are marked F1–F8 for correlation with the map in Fig. 3). Interpretations at depth are constrained by geometric criteria during cross-section construction other than balancing techniques as a result of lack of plane strain (see text for explanation).



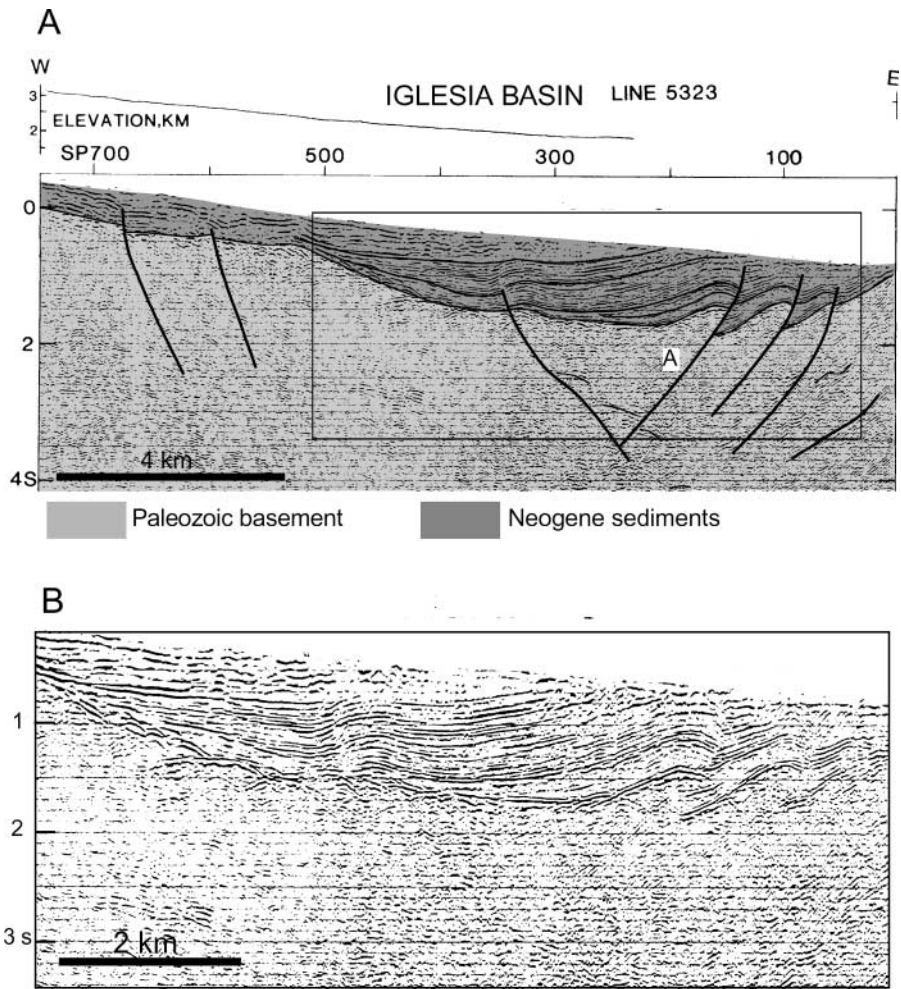


**Fig. 5.** (a) Map of the Neogene to Recent structures along the Rodeo deformation zone (location shown in Fig. 2a). Unshaded areas include Neogene and Quaternary undifferentiated sediments. Most of the area is covered by Quaternary alluvial fans; Miocene sediments appear mainly in the central part along the Iglesia River with minor outcrops along smaller subsidiary creeks. Lower Palaeozoic rocks are in grey. Box indicates the area shown enlarged in (b). (b) Distribution of axial traces of noncylindrical folds that are oblique to the fault trace. It should be noted that the axial traces of the anticline and syncline to the north converge and pass southwards into a single syncline trace. Sections 1–3 depict high-angle faults and related folds. Progressive unconformities are common within the basin sediments. Horizontal scale is equal to vertical scale. (c) Interpretation of seismic section across the Iglesia Basin depicting flower-type structures. TWT, two-way travel time.

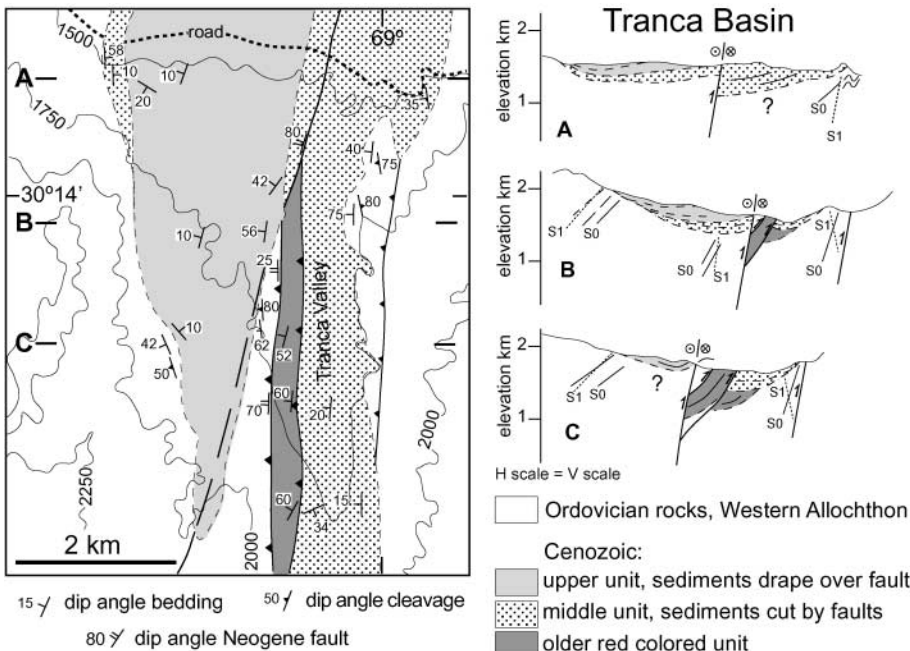
*Structures in the Tranca and Caracol basins.* The narrow intramontane Tranca and Caracol basins, south of the Jáchal River include Neogene sedimentary sequences of <1 km thickness (Figs 7 and 8). In both, there are high-angle faults with a dominant NNE trend, which are slightly oblique to the structures of the Palaeozoic basement. The oldest sediments within the basins are 'red beds' that are thought to be of Oligocene or Early Miocene age, on the basis of lithological correlations, and are interpreted to predate fault activity (Jordan *et al.* 1993). In both basins, fault-bound 'red-coloured' beds are unconformably covered by younger sediments (Figs 7 and 8), although correlations between the two basins and with the 'red beds' described by Jordan *et al.* (1993) are not clear. The younger sediments have been dated as Miocene (Jordan *et al.* 1993) and include progres-

sive unconformities and local infill of erosive palaeotopography suggesting syntectonic deposition. Fluvial and alluvial conglomerates dominate within these syntectonic sequences.

In the Tranca Basin a dominant west-dipping thrust with two minor east-vergent thrusts linked to it deforms three sedimentary packages that are separated by basin-wide unconformities (sections A, B and C in Fig. 7). Above the 'red-coloured' beds, the younger syntectonic sediments onlap the Palaeozoic rocks at both margins of the basin, and thicken towards the centre. They form broad, open synclines at both sides of the main fault. An upper package of syntectonic sediments drapes over the main fault and covers it towards the south (cross-section C in Fig. 7). The two minor east-vergent thrust planes have progressively shallower dips along strike towards the intersection with the high-angle

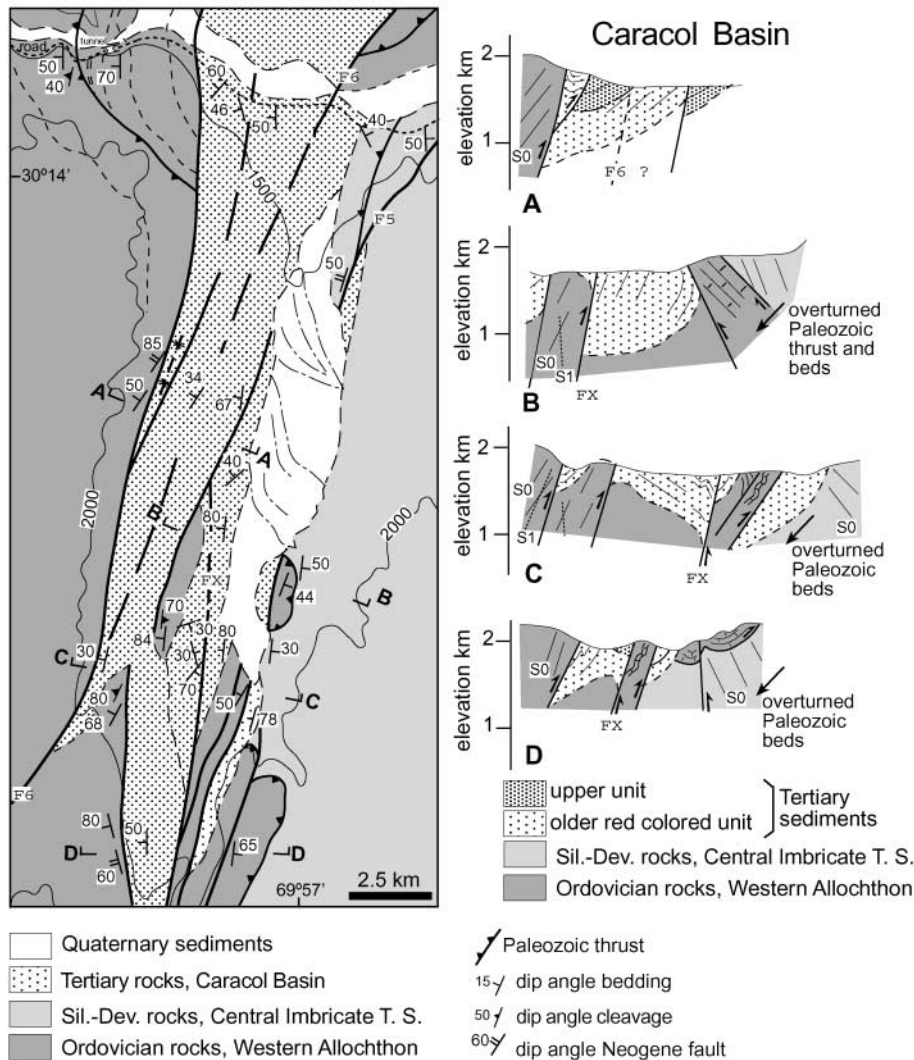


**Fig. 6.** (a) Interpretation of seismic profile 5323 across the Iglesia Basin. The large-scale structure is dominated by flower-type geometries that include both west- and east-dipping faults with normal and reverse apparent throw in two dimensions. Above fault A sediments thicken towards the fold crest. The flower-type structural style matches better the type and distribution of structures observed at the surface (see Fig. 5 for location of the seismic profile). (b) Enlarged part of the seismic profile for better resolution of the structure of basin sediments above the flower structure.



**Fig. 7.** Detailed map and cross-sections along the Tranca valley (location of maps are shown in Fig. 2a). Neogene sediments of this intramontane basin are partly covered along the valley centre by coarse Quaternary conglomerates associated with the ephemeral Tranca stream that are not represented in the map. Three tectostratigraphic units differentiated in the Tranca Basin are an older strongly red-coloured package that could predate faulting, a middle pink-grey-coloured coarse-grained unit affected by faulting, and an upper grey-coloured coarse-grained unit that covers the fault although it drapes over it. The angular unconformities within syntectonic sediments in sections A and B thickening towards the fault should be noted.





**Fig. 8.** Detailed map and cross-sections along the Caracol valley (location of maps is shown in Fig. 2a). Neogene sediments of this intramontane basin are partly covered along the valley centre by coarse Quaternary conglomerates associated with the ephemeral Caracol stream that are not represented in the map. The cross-sections represent two tectonostratigraphic units separated by a basinwide unconformity, an older red-coloured and an upper unit. These sedimentary packages are not correlated to the packages in the Tranca valley. F6 is marked for correlation with Figures 3 and 4. The contrasting apparent displacement on fault FX that appears in sections B, C and D should be noted. In all cross-sections horizontal scale is equal to vertical scale.

thrust. Geometric relationships between minor folds associated with these minor thrusts, the orientation of the fault planes and their intersections suggest a left-lateral component of displacement for the high-angle thrust.

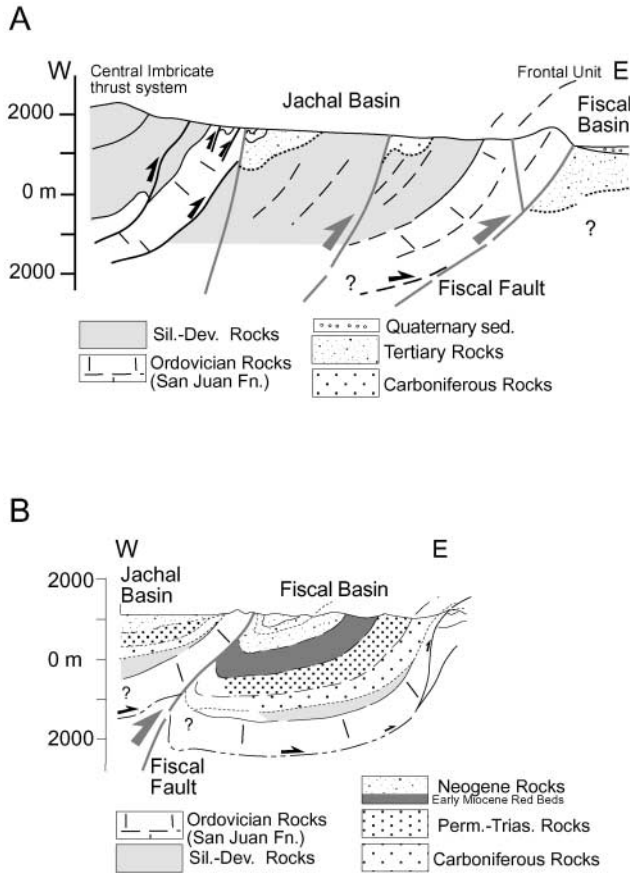
In the Caracol Basin, discontinuous rhomb-shaped outcrops of Palaeozoic basement rocks have faulted and unconformable contacts with surrounding Neogene basin sediments (Fig. 8). Apart from these outcrops, a large part of the basin is covered by Quaternary alluvial deposits. Fine-grained aprons of sediment spread downslope from the eastern Palaeozoic rocks, and in the centre coarser-grained conglomerates appear associated with the seasonal Caracol stream. Palaeozoic rocks in the western part of the basin are overthrust onto an asymmetric syncline of 'red beds' (sections A and C, Fig. 8), and locally overthrust westwards onto overturned 'red beds' of the eastern basin margin (section B, Fig. 8). Here the Palaeozoic stratigraphy and structure is overturned with a thin layer of carbonate rocks thrust over Siluro-Devonian clastic rocks.

Faults within the basin have both normal and reverse displacement and subvertical dip (Fig. 4). In the west, the Neogene sediments are folded into a tight upright syncline against the Palaeozoic rocks and show very gentle dips away from the fault.

The geometries of the sedimentary sequences, and of the structures in the study area, lead us to interpret the basin as part of a negative flower structure.

*Structures in the Jáchal and Fiscal basins.* In most of the Jáchal Basin, the Neogene sequences are covered by extensive Quaternary alluvial fan deposits. Narrow outcrops of Neogene strata are found only in two places. On the eastern margin of the basin starting to the north of the cross-section, a narrow strip of Upper Pliocene sediments progressively covers southwards the Permian, Carboniferous and Ordovician age sediments of the underlying west-dipping monocline (Furque *et al.* 1998). On the western margin of the basin, south of San José de Jáchal, the Neogene deposits appear along a narrow asymmetric syncline in faulted contact with carbonates of the San Juan Formation (Fig. 9a). This locality includes <800 m of mostly Lower Miocene sediments (Jordan *et al.* 1993). The Fiscal Fault trends subparallel to the trace of Ordovician sediments with a curved shape in map view. Along most of this curved trace Quaternary sediments appear in the immediate footwall, hampering the interpretation of the geometry at depth. In the hanging wall, Ordovician sediments dip 60–70° to the west along the trace of the cross-





**Fig. 9.** (a) Cross-section SW of San José de Jáchal that shows the Ordovician carbonates of the San Juan Formation in the most frontal thrust of the Central Imbricate thrust system (horizontal scale is equal to vertical scale). (b) A part of the section across the Fiscal Basin is presented for comparison of the geometry of the Fiscal Thrust and distribution of Neogene sediments. The low-angle unconformity at the base of Carboniferous sediments should be noted (horizontal scale is equal to vertical scale). Large arrows are on Neogene faults and small arrows on Palaeozoic thrusts. (See Fig. 3 for location of cross-section line.)

section shown in Figure 4. At the base, a fault gouge of several metres wide dips parallel to the hanging-wall beds. To the south, hanging-wall bedding dips 40–50° to the NW. The Fiscal Fault is a reverse fault that has brought to surface the Ordovician carbonates, placing them on top of Neogene strata of the Fiscal Basin.

Neogene sediments in the Fiscal Basin are up to 1200 m thick (Jordan *et al.* 1993), although thickness varies laterally as a result of unconformities. Most of the sequence appears to be folded together with the underlying Palaeozoic deposits into a wide synform (Fig. 9b). Inverted west-dipping conglomerates appear under the fault gouge of the Fiscal Fault, indicating the dragging of footwall sediments during faulting. The geometry of the synform at depth is constructed by taking into account sediment thickness and dip angles measured along the Huaco road section. To the east of the Fiscal Basin, the Ordovician carbonates are folded into a large box-shaped anticline. The eastern flank of the fold is subvertical and sediments of the Bermejo Basin appear to the east on a steep, east-dipping unconformable contact. However, south of the cross-section the

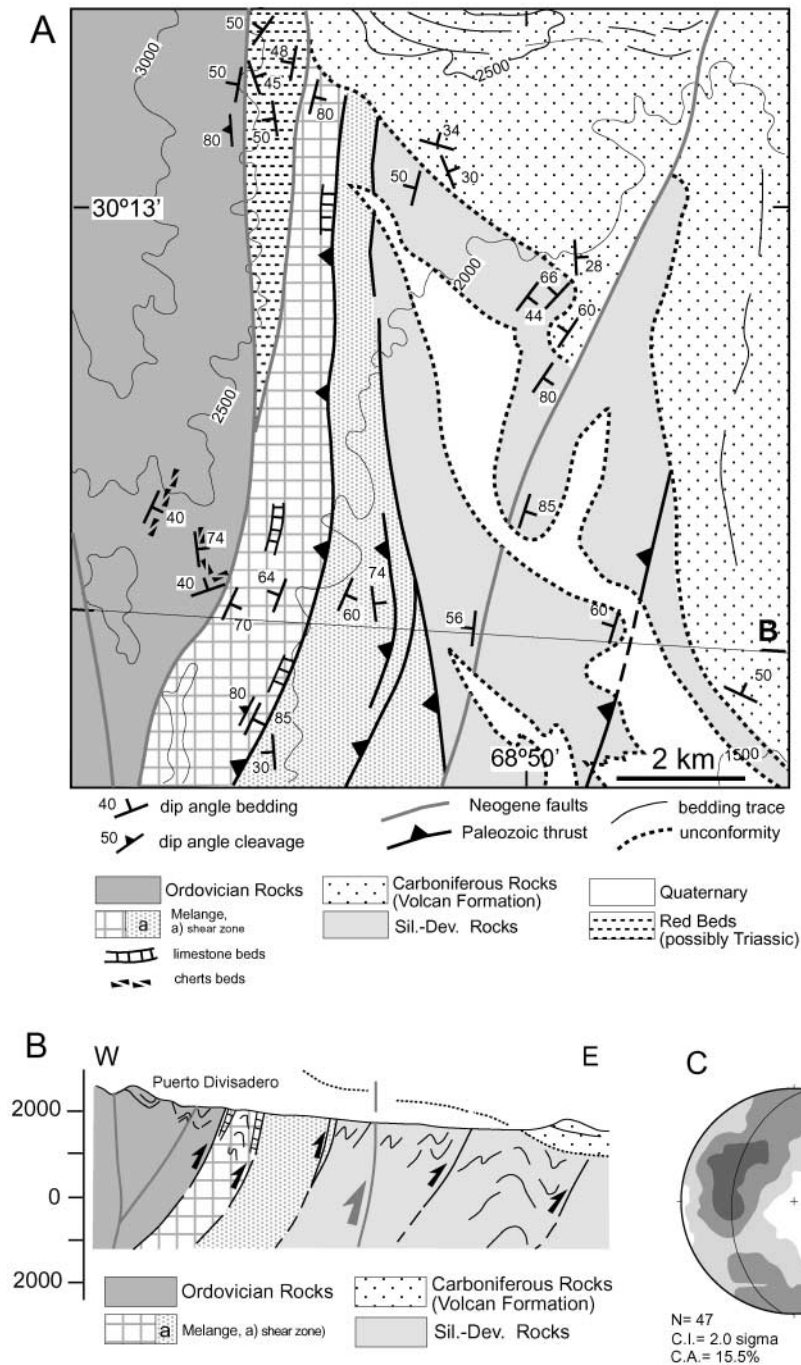
Ordovician carbonates are thrust onto the Bermejo Basin sediments along a NE-trending fault (Fig. 3), and the Neogene sediments of the Fiscal Basin that crop out form a west-dipping monocline that is unconformably covered by Upper Pliocene conglomerates (Jordan *et al.* 1993). This structure was also mapped in detail by Zapata & Allmendinger (1996a). These Upper Pliocene deposits wrap around into a south-plunging periclinal structure, indicating that sedimentation was synchronous with the tilting associated with bedding-parallel slip of the underlying homoclinal sequence. Differential bedding parallel slip on a steeply dipping multilayer below an unconformity produces folding in the sediments above the unconformity (Alonso 1989). This deformation could be related to activity of the Fiscal Fault in the last 2.7 Ma (Zapata & Allmendinger 1996a).

### Palaeozoic thrust systems

Within the Palaeozoic outcrops of the Jáchal River area, only one pre-Neogene deformation event has been recognized (Figs 3 and 4). The Palaeozoic structure consists of an east-vergent thrust stack that includes three units with varied stratigraphy and structural style (Figs 3 and 4). From west to east, the three tectonic units are: (1) the Western Allochthon, which deforms a large thickness of Ordovician age, mostly siliciclastic rocks; (2) a Central Imbricate thrust system that includes a large thickness of siliciclastic Siluro-Devonian rocks; (3) a Frontal Unit including a thinner sequence of Ordovician and Silurian rocks. The Central Imbricate thrust system and the Frontal Unit include Ordovician carbonates of the San Juan Formation (the oldest rocks cropping out in this section of the Precordillera) at the base of thrust sheets. In the central part of the Jáchal River area thrusts and folds deforming Ordovician to Devonian rocks are unconformably overlain by Middle to Upper Carboniferous rocks of the Volcan Formation (Furque 1979; Furque *et al.* 1998), placing an upper limit on the age of the Palaeozoic deformation (Fig. 10a and b).

*The Western Allochthon.* The Western Allochthon is an east-directed thrust stack that includes Ordovician metasedimentary rocks that underwent lower greenschist-facies metamorphism (von Gosen 1997). The whole series of sedimentary and volcanic rocks are included in the Upper Ordovician–Lower Caradocian Yerba Loca Formation (Furque 1979). There are outstanding lithological differences along the section that are grouped into four units separated by thrusts in the lithotectonic column (Fig. 2c).

Thinner-bedded, finer-grained sericitic siltstones and marls within well-stratified sandstone beds are frequent to the east (Los Tuneles area, Unit 3 in Fig. 2c), whereas thicker-bedded, coarser-grained sediments and conglomerates that commonly include sills and lenticular-shaped bodies of basic and ultrabasic rocks appear in the west (Cuesta del Viento area, Unit 4 in Fig. 2c). Volcanic rocks appear in the west interbedded within the coarser-grained sediments. These sediments are organized in shallowing upwards sequences that in some cases are topped with a layer of columnar jointed basalts. A 200 m wide continuous outcrop of pillow basalts occur along the road cut at Cuesta del Viento. These pillow basalts are in fault contact at the western edge of the allochthon, and are unconformably covered by Tertiary sediments of the Iglesia Basin (Figs 4 and 11a). Chaotic sediments including mass-flow deposits and large calcareous olistoliths within a siliciclastic matrix are included in two thin thrust sheets that bound the allochthon to the east along the road

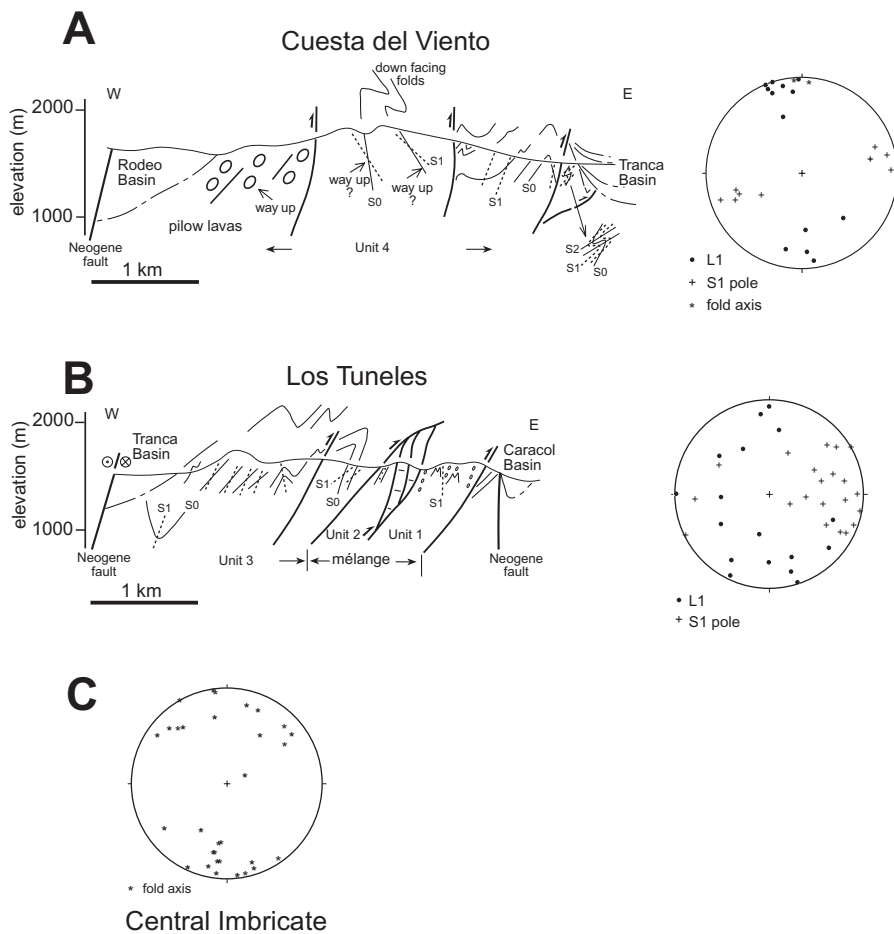


**Fig. 10.** (a) Geological map of the area north of San José de Jáchal showing dip angles that document the unconformable relation of Carboniferous sediments (dotted pattern) above the Devonian sediments (grey fill). (b) Cross-section NW of San José de Jáchal, where the thrusting of the Western Allochthon mélangé onto the Central Imbricate thrust system is not obscured by Neogene faulting, and includes the unconformable Carboniferous sediments on the Central Imbricate thrust system (location shown in Fig. 3). The interpreted thrust in the east, beneath the unconformity, is considered to correspond to the northward prolongation of the most frontal thrust of the Central Imbricate thrust system that appears in the section of Figure 4. (c) Stereoplot of curved fold axes within the shear zone (C.I., contour interval; C.A., contouring area).

section (Units 1 and 2 in Fig. 2c). These have been previously interpreted as forming a sedimentary mélangé (von Gosen 1997).

The Western Allochthon is folded by a kilometre-scale anti-form–synform fold pair that possibly developed during the latest stages of emplacement, and that has been deformed by later Neogene faulting (Fig. 4). The internal structure of the Western Allochthon is best displayed at Cuesta del Viento and Sierra de los Tuneles along the Jáchal River road cut (Figs 4 and 11). At Cuesta del Viento a 5 km scale antiform is cored by a fault. Along its western flank a large outcrop (>200 m along the road section) of pillow basalts dip moderately westwards (Fig. 11a).

The eastern flank is marked by a narrow, fault-bounded zone of steeply east-dipping bedding and east-dipping cleavage. The asymmetric Z-shaped minor folds in this part of the section have been previously interpreted as west-vergent structures because of the attitude of the cleavage (Ramos 1988; von Gosen 1997). Way-up criteria, such as small-scale graded bedding, are not conclusive in this area, but the Z shape of the minor folds, the overall fining eastward of the bedding, and other geometric criteria such as the normal position of the stratigraphy across the remaining section, suggest that these folds can be better interpreted as downward-facing minor folds on the eastern flank



**Fig. 11.** (a) Detailed cross-section of the Western Allochthon at Cuesta del Viento (Unit 4 in Fig. 2) and stereoplot of minor structures. The fault between the pillow lavas and the sediments deformed by metre-scale down-facing folds is interpreted to obliterate the core of a large antiform (see text for interpretation of way up in this part of the section). The thrusts within the Ordovician rocks are interpreted as Palaeozoic structures, because they do not seem to cut the contact with Neogene sediments to the north (see map in Fig. 3). Reactivations by Neogene age deformation cannot be ruled out and may have caused the open folding of that contact (see also Fig. 5a). (b) Detailed cross-section of the Western Allochthon at Los Tuneles and stereoplot of minor structures. Units 1 and 2 constitute a tectonic mélangé and Unit 3 forms the frontal part of the allochthon. The thrusts mapped within the Ordovician rocks are interpreted as Palaeozoic structures. (c) Stereoplot of fold axis within the Central Imbricate thrust system along the section shown in Figure 4. Changes in the orientation of structures between stereoplots along the Jáchal River area cross-section are interpreted mostly as due to overprinting caused by superimposed Neogene deformation.  $S_0$ , bedding;  $S_1$ , axial planar cleavage;  $S_2$ , local crenulation cleavage;  $L_1$ , intersection lineation.

of a larger antiform. This antiform would fold the large normal limb of an east-vergent structure (see below). The remaining Cuesta del Viento outcrop contains upright folds with a near-vertical axial planar cleavage ( $S_1$ ).  $S_1$  shows varied dips locally as a result of cleavage refraction caused by the presence of mafic sills and lenticular-shaped bodies of basic and ultrabasic rocks interstratified within less competent rocks (stereoplot in Fig. 11a). Locally, a weakly developed crenulation cleavage ( $S_2$ ) has been found near minor faults. The three thrusts that cut through the allochthon in this section are interpreted as Palaeozoic. They are not seen to cut through younger sediments (Fig. 3).

At Sierra de los Tuneles, the frontal part of the allochthon consists of an east-vergent antiform with a wide normal limb and an overturned narrow frontal limb (Unit 3 in Fig. 11b). The normal limb includes east-vergent thrusts and metre-scale, minor asymmetric folds with a strong axial planar cleavage. Locally, the cleavage is deformed by centimetre-scale shallowly dipping kink bands. A weak crenulation cleavage is developed locally. The folds in the normal limb tighten towards the frontal part of the allochthon, where the overturned limb is cut by the west-dipping basal thrust. The basal thrust overrides the mélangé that constitutes the sole of the Western Allochthon (Units 1 and 2 in Fig. 11b). Along the road cut, the mélangé consists of two units that are laterally discontinuous. A duplex structure, which includes mostly thin-bedded limestones deformed by non-cylindrical tight folds and thrusts (Unit 2), overrides a series of

syntectonic mass-flow deposits that display widespread slumping, and includes polymictic conglomerates with well-rounded quartzitic clasts (Unit 1). These mass-flow deposits are deformed by metre-scale upright folds and a weakly developed cleavage within a wide synformal structure. This synform is in fault contact with Cenozoic sediments of the Caracol Basin in the road section.

The structural relationship between the Western Allochthon and the Central Imbricate thrust system to the east is seen near the area called Puerto Divisadero (Fig. 10a and b). Here Ordovician sandstones and cherts intruded by mafic bodies are thrust onto a sequence that includes many carbonate beds, and that displays a shear zone at the base. The shear zone is more than 1 km wide, and is defined by a west-dipping dominant foliation including bands with centimetre-scale sheath folds. The majority of plunge values indicates top to the ESE for the thrusting direction in the present position (Fig. 10c). However, some modification of the original orientations by superposed Neogene faulting cannot be discounted. Immediately beneath the shear zone, east-verging folds and thrusts without cleavage deform Silurian to Devonian clastic deposits of the Central Imbricate thrust system.

*The Central Imbricate thrust system.* A large, continuous, outcrop of Silurian to Devonian clastic deposits exposed between the Caracol Valley and San José de Jáchal is deformed by a system of east-directed imbricate thrusts and related fault



propagation folds (Fig. 4). The imbricate thrusts are interpreted to merge into a sole thrust located at the base of a thin layer of Ordovician age carbonates of the San Juan Formation. In the mapped area, the Lower Ordovician carbonates of the San Juan Formation are only seen in the eastern edge of the Central Imbricate thrust system (Fig. 9a).

Folding at different scales is pervasive within the Central Imbricate thrust system. The upper part of the Devonian series occupies the core of the larger synclines found to the south of the Jáchal river (Fig. 3). Towards the eastern part of the cross-section, well-exposed, kilometre-scale fault propagation folds are found. In contrast, kilometre-scale folds are less common towards the west (Fig. 4, segment B). The variations of fold size appear to be controlled by differences in bedding thickness within the multilayer, and also by the existence of small-scale thrusting. Most folds in outcrop have a fault propagation fold geometry that varies from common chevron-type with  $<90^\circ$  interlimb angle to more open cylindrical folds. Locally, fault-bend folds with a box-shaped geometry are also found in relation to hanging-wall thrust ramps.

The imbricate thrust system is breached by a later Neogene high-angle fault that juxtaposed two pieces of it (F4 in Fig. 4). To the east of the breaching fault the original position of Palaeozoic structures seems better preserved, allowing more confident interpretations of the structure at depth. Two major thrusts can be distinguished by the existence of two bands of Ordovician carbonates mapped to the south of the transect studied here (Furque *et al.* 1998). These thrusts are interpreted to merge into the basal thrust. Geometric constraints during cross-section construction indicate that the basal detachment may flatten in this part of the section at a depth no greater than 3 km. To the west of the breaching fault, dominantly thin-bedded clastic sediments are deformed by widespread overturned folds and thrusts (Fig. 4, segment B). Back-rotation of the original folds and thrusts, in places taking the limbs to an overturned position, are interpreted to be an effect of Palaeozoic forward imbrication and superposed Neogene deformation (Fig. 4). However, Neogene folds or cross-folding effects may have occurred that are difficult to distinguish within this thinly bedded sequence. The lithology within this part of the imbricate structure resembles that of the Silurian and lower part of the Devonian. Outcrops of the basal Ordovician carbonates and the basal thrust are lacking in this western piece of the imbricate structure, and the interpretation of the structure at depth is not well constrained. Sporadic outcrops of carbonates along the eastern margin of the Caracol Basin may correspond to the San Juan Formation that has been brought to the surface by Neogene faulting. However, we favour the interpretation of these carbonates as pieces of the tectonic unit at the sole of the Western Allochthon (Fig. 8).

Structural relationships between the Central Imbricate thrust system and the Frontal Unit are obscured by the Cenozoic deposits along the Jáchal Basin, and are not resolved with the available data. There are marked differences between the Palaeozoic stratigraphic sequence present in the Central Imbricate thrust system and that within the Frontal Unit (Fig. 2c). These differences may argue for a possible large displacement across the frontal thrust of the Central Imbricate thrust system (see below). However, they may be also due to large displacements along Neogene faults.

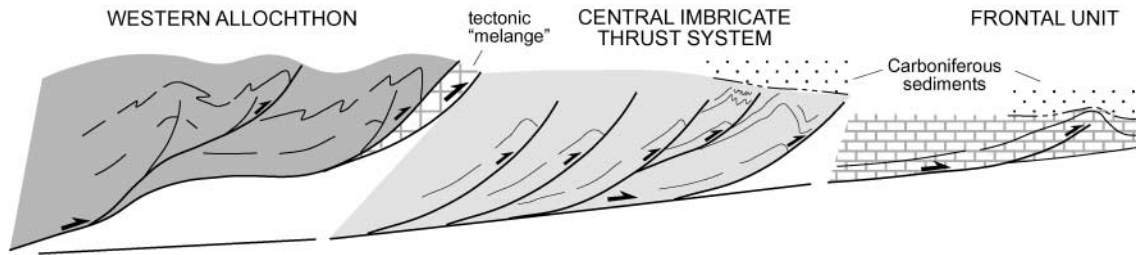
*The Frontal Unit.* The Frontal Unit includes the easternmost outcrops of Palaeozoic sediments in the Jáchal River area. These consist of two bands of thick Ordovician carbonates that are well exposed along the Huaco River section (Figs 3 and 4). Carboni-

ferous deposits of the Volcan Formation (Furque *et al.* 1998) appear in most places directly above the carbonates along a low-angle unconformity. Thin Silurian and Devonian clastic sediments are found only in a narrow strip along the eastern margin of the Fiscal Basin south of the section.

The deformation style in the Frontal Unit is markedly different from that of the Palaeozoic thrust units described above. Carboniferous sediments and Neogene deposits of the Fiscal Basin are folded together with underlying Ordovician rocks, indicating that Palaeozoic deformation was probably minor within this unit. However, the low-angle basal Carboniferous unconformity in the eastern flank of the Fiscal Basin indicates the occurrence of some deformation of underlying beds prior to deposition of Carboniferous sediments. This deformation could have been accomplished by formation of a low-amplitude thrust-cored anticline. In this scenario, the minor thrust seen at the core of the frontal box-shaped anticline in Figure 4 is interpreted as corresponding to the Palaeozoic thrust system that merges into a basal décollement beneath the Ordovician carbonates. This basal décollement would continue at the base of the Ordovician carbonates beneath the Fiscal and Jáchal basins to join the basal thrust beneath the Central Imbricate thrust system (Fig. 12). We interpret the Palaeozoic thrust front as a protothrust, in which slip along the basal thrust dies out into a low-amplitude thrust-cored anticline at the deformation front of the Palaeozoic thrust stack. The Fiscal Fault is interpreted to have breached through a flat-lying part of the Palaeozoic thrust unit. The kilometre-scale folds that show a box-like geometry along the cross-section could be the result of superposed folding and amplification associated with the two high-angle Neogene faults that breach through the Frontal Unit (Fig. 4).

## Discussion

The geology that crops out along the Jáchal River area includes a sedimentary record from the Early Ordovician to the present, with a large gap during the Jurassic to Early Tertiary (Jordan *et al.* 1993; Furque *et al.* 1998). The Early Palaeozoic sequences are mostly shallow marine with deeper clastic sequences in the western part (Astini *et al.* 1995; Keller 1999), and are unconformably covered by Carboniferous continental to shallow marine clastic sequences in the east (Furque *et al.* 1998). The Cenozoic sequences are mostly Neogene to present continental sediments (Beer *et al.* 1990; Jordan *et al.* 1993). Our structural analysis indicates that sedimentation records two episodes of contractional deformation, one in the Palaeozoic and the other in the Neogene to present. The earlier resulted in large amounts of shortening and the later included transpressive displacements that mildly overprint previous structures. The combined effects of early contraction and superposed transpression impose many uncertainties on the interpretations of the structure and in establishing east-to-west structural and stratigraphic correlations along a single transect. Uncertainties were encountered during the construction of the cross-section along the Jáchal River area, mostly in the interpretation at depth of both the Palaeozoic and Neogene structures. Section balancing geometric constraints are not applicable because 'plane-strain' cannot be assumed. This also hampers the calculations of the amount of shortening. In addition, the lack of pre-Neogene undeformed reference horizons hinders calculations of displacements along Neogene faults. Structural studies along parallel sections to the north and south are necessary to reduce these uncertainties.



**Fig. 12.** Idealized structure of the Palaeozoic thrust wedge during Carboniferous times. Deformation style in the western part (Western Allochthon) includes tight folding with associated axial planar cleavage and slight metamorphism. Imbricate thrusts and fold propagation folding appear in the east (Central Imbricate thrust system) and shortening dies out at a protothrust (Frontal Unit). In this interpretation the *mélange* corresponds to the sole of the Western Allochthon (tectonic *mélange*), which could be prolonged further beneath its basal thrust. Later Neogene deformation and breaching faults caused juxtaposition of parts of the Palaeozoic thrust wedge that were laterally and vertically apart. This implies that the units, dimensions and geometries displayed in this idealized thrust wedge could vary greatly from those in a non-disturbed, originally continuous east–west Palaeozoic section.

### Palaeozoic deformation

The present architecture of the Palaeozoic structures along the Jáchal River section indicates that Palaeozoic shortening was accomplished by east-directed thrusting and folding. The Palaeozoic structures are interpreted to form a thrust wedge made up of three units with structural styles that indicate development of shallower deformation conditions from west to east (Fig. 12). The deeper deformation conditions occurred in the Western Allochthon, the Central Imbricate includes structural styles typical of upper crustal foreland thrust and fold belts, and the Frontal Unit is interpreted to register minor Palaeozoic deformation at the front of the thrust wedge. Structural relationships between these three units of the thrust wedge are masked by later, Neogene sedimentation and breaching faults. Sharp structural and stratigraphic differences between the thrust units are accentuated by Neogene-age oblique juxtaposition of pieces of the thrust wedge that originally were laterally and vertically separated.

The Western Allochthon structure is unlikely to be of Neogene age, given that Neogene deformation conditions were much shallower, as indicated by the associated continental-facies sedimentation (Beer *et al.* 1990; Jordan *et al.* 1993). The allochthon, at the rear of the Palaeozoic thrust wedge, includes internally strained and slightly metamorphosed sediments that are different from the sediments in the other units (Astini *et al.* 1995; von Gosen 1997). The stratigraphic differences are thought to be related to Ordovician rifting at the western edge of a carbonate platform (see Keller 1999, for a review), and structural differences are due to Palaeozoic thrusting and telescoping combined with Neogene faulting. The sediments within the thin tectonic units at the sole of this allochthon (the ‘*mélange*’ of von Gosen 1997) contain rocks with a variety of ages including Early Cambrian and Early Ordovician carbonates, Llanvirn shales, and ages as young as Caradoc have been proposed (Keller 1999). The simplest interpretation of the duplex structure in carbonates at Los Tuneles (Unit 2) is that they represent material scraped off the underlying continental margin as the Western Allochthon was thrust eastwards. Previous interpretations considered them as part of a sedimentary *mélange* related to the western slope facies of a Cambro-Ordovician passive continental margin (Gonzalez Bonorino & Gonzalez Bonorino 1991), as related to extensional faulting in the western margin of the continental platform (von Gosen 1997), or as belonging to the continental rise (Keller 1999). In our interpretation, some off-scraped carbonate material

(Unit 2) was later attached to syntectonic deposits (mass-flow deposits, Unit 1) and both were finally underplated to the toe of the Western Allochthon, forming a tectonic *mélange*.

The remaining central and frontal units of the thrust wedge show structural styles developed at shallower crustal conditions than those in the Western Allochthon (Fig. 12). Thin-skinned deformation, with thrust imbrication and related folding above a detachment at the base of Ordovician carbonates, appears to have resulted in significant shortening within the Central Imbricate prior to deposition of Carboniferous sediments, in contrast to that of the Frontal Unit. This eastern part of the section exhibits mostly Neogene deformation (Zapata & Allmendinger 1996*b*). However, some Palaeozoic shortening occurred as evidenced by the low-angle unconformity beneath Carboniferous sediments. To explain this, we interpret the Frontal Unit as a protothrust at the front of the Palaeozoic thrust wedge, developed ahead of an emergent thrust system in the Central Imbricate.

The precise age of Palaeozoic shortening along the Jáchal River area is not well constrained. The existence of pre-Carboniferous contraction along this area was first demonstrated by Furque (1979), based on mapped and stratigraphic evidence. Ramos *et al.* (1986) proposed that intense deformation in the western Precordillera occurred during Mid- to Late Devonian time, and von Gosen (1997) described Devonian to pre-Late Carboniferous contractional structures in the eastern Jáchal area. Astini *et al.* (1995), used stratigraphic and palaeontological correlations to propose that the Precordillera started to collide with the western Gondwana margin during Early Ordovician times. The low greenschist-facies metamorphism in the Western Allochthon was assigned a Late Silurian–Early Devonian age by correlation with rocks in the western Precordillera to the south (von Gosen 1997). In the southwestern Precordillera, the previous K–Ar dates and new  $^{40}\text{Ar}/^{39}\text{Ar}$  dating led Davis *et al.* (1999) to propose an Early to Mid-Devonian age for the synmetamorphic top-to-the-east ductile deformation that juxtaposed pre-Carboniferous rock units. However, age correlations between the Western Allochthon and tectonic units to the south are uncertain until the structural relationship between the two is established.

Our data along the Jáchal River area indicates a process of eastward emplacement of an east-propagating thrust wedge that was completed before sedimentation of the Mid- to Late Carboniferous Volcan Formation (Furque 1979; Furque *et al.* 1998). Some minor deformation at the frontal part of the thrust wedge could be slightly younger. In our section, the youngest

sediments cut by the shear zone at the base of the Western Allochthon belong to the Early Devonian Talacasto Formation (Furque *et al.* 1998). We found no structural evidence for Ordovician age contractional deformation.

The data presented here raise questions regarding the tectonic context in which this Palaeozoic thrust wedge formed. Previously, the deformation of the Precordillera has been included within models of a long-lasting process of terrane accretion related to east-directed subduction (i.e. Ramos *et al.* 1986; Ramos 1988; Astini *et al.* 1995). The main argument for east-directed subduction was the west vergence of structures along the Jáchal River section and other areas of the Western Precordillera. At Cuesta del Viento, however, we suggest that the previously defined west-vergent folds can be best interpreted as Z-shaped down-facing minor folds on a larger east-vergent structure. Furthermore, west-vergent folds found in the central part of the section (von Gosen 1997) can be interpreted as back-rotated, east-vergent folds with the rotation resulting from forward imbrication of thrusts and superposed Neogene faulting. In the Western Precordillera, south of our area, Davis *et al.* (1999) and Gerbi *et al.* (2002) also reinterpreted previously proposed Palaeozoic west-vergent structures to have east vergence. Along the Jáchal River section, the internal distribution of strain within the thrust wedge, with stronger deformation in the west and lesser deformation in the east, is also evidence for east-directed emplacement. These geometries fit within a context of west-directed subduction and underthrusting of a continental basement similar to thin-skinned thrust and fold belts in the external areas of other orogens. A Palaeozoic west-directed subduction model has been proposed by Davis *et al.* (1999) and Gerbi *et al.* (2002) as a possible simplest tectonic scenario for emplacement of highly strained east-directed allochthonous units in the western margin of the Precordillera. The same tectonic scenario was previously suggested by Astini *et al.* (1995), based on the absence of volcanic or pyroclastic arc-derived rocks in the Precordillera.

### *Neogene deformation*

The current interpretation of the Precordillera structure was that of a thin-skinned thrust belt (Allmendinger *et al.* 1990; von Gosen 1992). This interpretation stems from the early recognition of an Ordovician carbonate layer that is repeated at the base of thrust plates in the central Precordillera (i.e. Baldis & Chebli 1969). However, Carboniferous sediments unconformably cover the thrusts and folds developed in underlying Devonian sediments in the central part of the Jáchal River area, providing an unequivocal Palaeozoic age, as was recognized by Furque (1979).

The Neogene structure of this part of the Precordillera is characterized by high-angle, NE-striking, linked fault system. The linkage is apparent in the central and western part of the section, and widespread Quaternary sedimentation masks such connections in the east. The fault system appears to control the present distribution of basins and ranges, dividing them into rhomb-shaped domains. Most faults have a component of oblique slip and flower-type structures are interpreted at depth in the Iglesia, Tranca and Caracol basins based on several lines of evidence. These include the structure within basin sediments, which does not resemble the structural style typically related to thin-skinned thrust systems, the coexistence of faults with reverse and normal throw, the change in dip orientation of faults and apparent vertical throw along strike. Recent studies also highlight the importance of strike-slip deformations in nearby areas

(Introcaso & Ruiz 2001). However, some Neogene basins appear to be bounded at their western margins by north–south-striking thrusts (Allmendinger *et al.* 1990). Commonly, the sediments appear subvertical or even overturned as a result of dragging beneath the thrusts. Fault activity ranges from 20 Ma to the present, including simultaneous motion and out-of-sequence thrusting (Jordan *et al.* 1993).

Neogene deformation is superposed onto earlier Palaeozoic structures without substantially overprinting them. Neogene faults crosscut the earlier structures, and associated deformation partitioning causes rigid block rotations, local refolding and reactivation of some previous structures. These superposed deformations are thought to be responsible for the apparent western vergences of some Palaeozoic folds, and for differences in the strike of Palaeozoic structures between adjacent Neogene fault blocks. Open and non-cylindrical folds that cause a curvature of Palaeozoic surfaces (bedding and faults) and fold axes are found locally, suggesting some internal deformation of fault-bounded blocks. Reactivation of previous anisotropy such as bedding or fault planes, and amplification of previous folds is also found.

The Neogene fault system appears to be deep rooted, yet caused less shortening than the 60–70% previously proposed for the Jáchal river area (Allmendinger *et al.* 1990). Our section suggests shortening values of the order of 15–20% as indicated by the open folding in Neogene sediments and high angle of main faults. A detachment at 15 km depth was inferred from interpretations of depth to pre-Palaeozoic basement in seismic profiles in the Bermejo foreland basin and the Eastern Precordillera (Allmendinger *et al.* 1990; Zapata & Allmendinger 1996a). However, the breaching fault system along the Jáchal River area could merge at depth into a zone of distributed deformation rather than a discrete detachment surface, which may be explained by the existence of crustal seismicity beneath the Precordillera (Smalley *et al.* 1993; Pardo *et al.* 2000).

Neogene deformation in the Jáchal River area could fit within a model of transpressive deformation that caused net orogen longitudinal extension and net orogen perpendicular compression. As a result, several continental-facies basins developed within the fault set. The north–south-oriented right-lateral Tigre Fault that bounds the Precordillera along the Iglesia Calingasta Valley for more than 120 km (Siame *et al.* 1997) may be the major structure to which the transpressive fault system of the Jáchal River area is linked. This intracontinental Neogene to present transpressional deformation may be connected to the kinematics and morphology of the subduction in this segment of the Andes (Brooks *et al.* 2003). Somoza (1998), in a review of the available data relative to Nazca–South America relative motions, considered that the convergence azimuths since 20 Ma ago have been slightly oblique to the Chile Trench, including azimuth values between 82° and 69°. The transpression may be governed by both the oblique subduction (DeMets *et al.* 1994; Somoza 1998) and the flat geometry of the subducting plate (Cahill & Isacks 1992). Also, analogue and numerical modelling suggest that oblique convergence may be an important factor governing strain partitioning (Pinet & Cobbold 1992; Chemenda *et al.* 2000). The oblique convergence combined with the increase of interplate coupling in flat subduction areas appear to enhance strain partitioning far inboard of the trench (Gutscher *et al.* 2000). This transpressive tectonic model for the foothills of the Andes makes this section of the Precordillera ‘different’ from other well-known models of thin-skinned deformation at foreland thrust belts. The lack of a flat-lying, older sedimentary package ready to be



transported and shortened above a general décollement level also played an important role in the resulting deformation style.

## Conclusions

Along a west–east cross-section of the complete Precordillera in the Jáchal River area, near 30°S latitude, two major sets of structures reveal differing deformation styles that have been superimposed during the Palaeozoic to present tectonic evolution of this sector of the Andes.

(1) A pre-Late Carboniferous east-verging thrust stack consists of three main thrust units that exhibit important variation in structural style and stratigraphy, possibly as a result of large horizontal displacements. The thrust wedge includes at the rear the Western Allochthon, which consists mostly of clastic Ordovician rocks folded by large-scale asymmetric, east-verging folds with a well-developed axial planar cleavage and very low grade metamorphism. The Central Imbricate thrust system deforms mostly Siluro-Devonian rocks in a system of imbricate east-verging thrusts and associated fault propagation folds. The imbricate thrusts merge into a detachment near the base of the Ordovician carbonates. The Palaeozoic deformation in the Frontal Unit possibly consists of a prot thrust structure at the core of an open anticline.

(2) A Neogene set of steep transpressive faults have uplifted and breached the previous thrust wedge. This Neogene fault system has a number of associated intramontane basins. On the basis of outcrop and seismic data, Neogene structures within most intramontane basins are interpreted to have flower-type geometries. It is common that within the Western Allochthon and Central Imbricate thrust system, the syntectonic sediments within the intramontane basins unconformably onlap the Palaeozoic units at the basin margins. In some cases reactivation of Palaeozoic thrust faults resulted in overthrusting of the basin sediments, and in other cases progressive unconformities attest to the continuous uplift at the unconformable contact. Neogene overprinting of Palaeozoic structures produced backtilting and overturning of folds in the older thrust system.

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