ACTA GEOLOGICA HISPANICA, v. 34 (1999), nº 2-3,p. 185-196

Oppositely-verging thrusting structures in the North Argentine Andes compared with the German Variscides

Estructuras con vergencia opuesta en Los Andes del Norte Argentino, comparadas con el Varisco de Alemania

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ABSTRACT

The Andes of north Argentina and the german Variscides, in spite of their different ages and geological settings, are considered good examples of convergent orogens displaying oppositely vergent thrusts. The back-thrusting is related to deep seated blind thrusts forming conjugate fault combinations which are significant in upper and mid-crustal shortening. Deep-seated conjugate fault systems in the Variscides were detected in reflection seismic profiles and in the Andes of north Argentina by mapping and through electrical conductivity investigations.

In the Variscides conjugate fault systems may be recognized at every scale in the upper crust and they form giant combinations in the lower crust. In the Andes the enhanced conductivity zones within the lower crust are arranged in conjugate systems, that could represent crustal detachments associated with Nazca plate subduction.

In the Andes crustal conjugate fault structures similar to those described in the Variscides, could be present under the west verging eastern border of the Pampean Ranges and beneath the southern Subandean Ranges (Santa Bárbara System). The other oppositely-vergent belts of the north Argentine Andes show fan arrangements similar to those recognized in other orogenic zones such as the Alps and the Pyrenees.

The comparison with other well-studied orogens allows speculation about the deep structure of the north Argentine Andes, where there is insufficient crustal information. The Variscides and other orogens whose deep structure has been investigated by deep seismic reflection profiles, suggest that in the oppositely vergent orogens the back-thrusting fronts are systematically associated with crustal-scale thrusting. In the case of the Andes this could imply that significant lithospheric thrusting may be present below the big back-thrusting fronts of the Eastern Cordillera and Pampean Ranges.

Key words: Andes-Variscides, Conjugate crustal detachments, Underthrusting, Crustal thickening

RESUMEN

Los Andes del Norte argentino y el Varíscico de Alemania, a pesar de sus diferentes edades y situación geológica, se consideran buenos ejemplos de orógenos convergentes con cabalgamientos con vergencia opuesta. Los retrocabalgamientos están relacionados con cabalgamientos ciegos profundos con los que componen sistemas conjugados que son significativos en el acortamiento de la corteza media y superior. Tanto en los Andes del Norte argentino como en los Variscides se detectaron sistemas profundos de fallas conjugadas, en los primeros mediante cartografía geológica e investigaciones de conductividad eléctrica y en los segundos mediante sísmica de reflexión.

En los Varíscides se pueden reconocer estructuras conjugadas a todas las escalas en la corteza superior y combinaciones gigantescas en la corteza inferior. En los Andes las zonas de alta conductividad eléctrica, situadas en la corteza inferior, están ordenadas en sistemas conjugados que pueden representar grandes fallas corticales asociadas a la subducción de la placa de Nazca. Debajo del borde oriental de las Sierras Pampeanas y del tramo Sur de las Sierras Subandinas (Sistema de Santa Bárbara) que tienen vergencia hacia el Oeste, es probable que exista una combinación conjugada a escala cortical similar a las descriptas en los Varíscides. Los otros cinturones con vergencia hacia el Este y hacia el Oeste de los Andes del Norte argentino muestran dispositivos en abanico similares a los reconocidos en cinturones orogénicos como los Alpes y los Pirineos.

La comparación con orógenos cuya estructura profunda está bien estudiada permite especular sobre la estructura profunda de los Andes del Norte argentino donde la información cortical es aún insuficiente. Los Varíscides y otros orógenos cuya estructura ha sido investigada con sísmica de reflexión profunda sugieren que los frentes retrovergentes están sistemáticamente asociados con cabalgamientos corticales profundos. En el caso de los Andes esto implicaría que debajo de los frentes retrovergentes de la Cordillera Oriental y de las Sierras Pampeanas pueden existir cabalgamientos litosféricos significativos.

Palabras Clave: Andes-Varíscides. Corrimientos corticales conjugados. Bajo-corrimientos. Engrosamiento cortical.

INTRODUCTION

This study presents the first results of comparative investigations between the tectonics of the Central Andes of North Argentina and other well-documented orogens such as the Variscides. The aim of the investigation is to develop a better understanding of the oppositely dipping thrusts in these belts. The External Variscides of Central Europe were selected because in this Paleozoic orogenic belt the structure is particularly well known from coal mining data and deep seismic reflection profiles. In the Central Andes well exposed thrusts showing different directions of thrusting have been recognized by surface geological mapping. The comparative studies with other well studied orogens showing a similar surface structure is particularly useful for the Andes because in this region deep seismic reflection studies are scarce and crustal-scale information is poor. Conversely the Andes expose deeper tectonic levels than the Variscides where these levels can be studied only through indirect methods.

The eastern margin of the Central Andes and the northern margin of the Central European Variscides are both associated with foreland basins; the former during Mesozoic and Tertiary time; the latter during Devonian through Permian time. Both external fold belts show thrusting directions generally towards their respective forelands. However there are significant back-thrusts in both orogens.

STRUCTURE OF THE ANDES

The central belts of the north Argentine Andes comprise the Eastern Cordillera and the Pampean Ranges (Fig. 1), where southward of 23º S doubly-vergent structures are widely developed. The tectonic evolution of these belts culminated between the Pliocene and the Lower Pleistocene. The oppositely dipping fault structures were recognized by surface geological mapping in previous investigations (e.g. González Bonorino, 1950a,b,c; Ruiz Huidobro, 1955; Schwab, 1970; Mon, 1976a,b; Grier, 1990; Grier et al., 1991; Cahill et al. ,1992).

The Eastern Cordillera is a basement-involved fold and thrust belt following the eastern side of the Puna high plateau. The entire orogen was transported eastward and thrust over the Subandean ranges. Its highest peaks are over 5000 m. It consists mainly of sheets of faulted Pre-

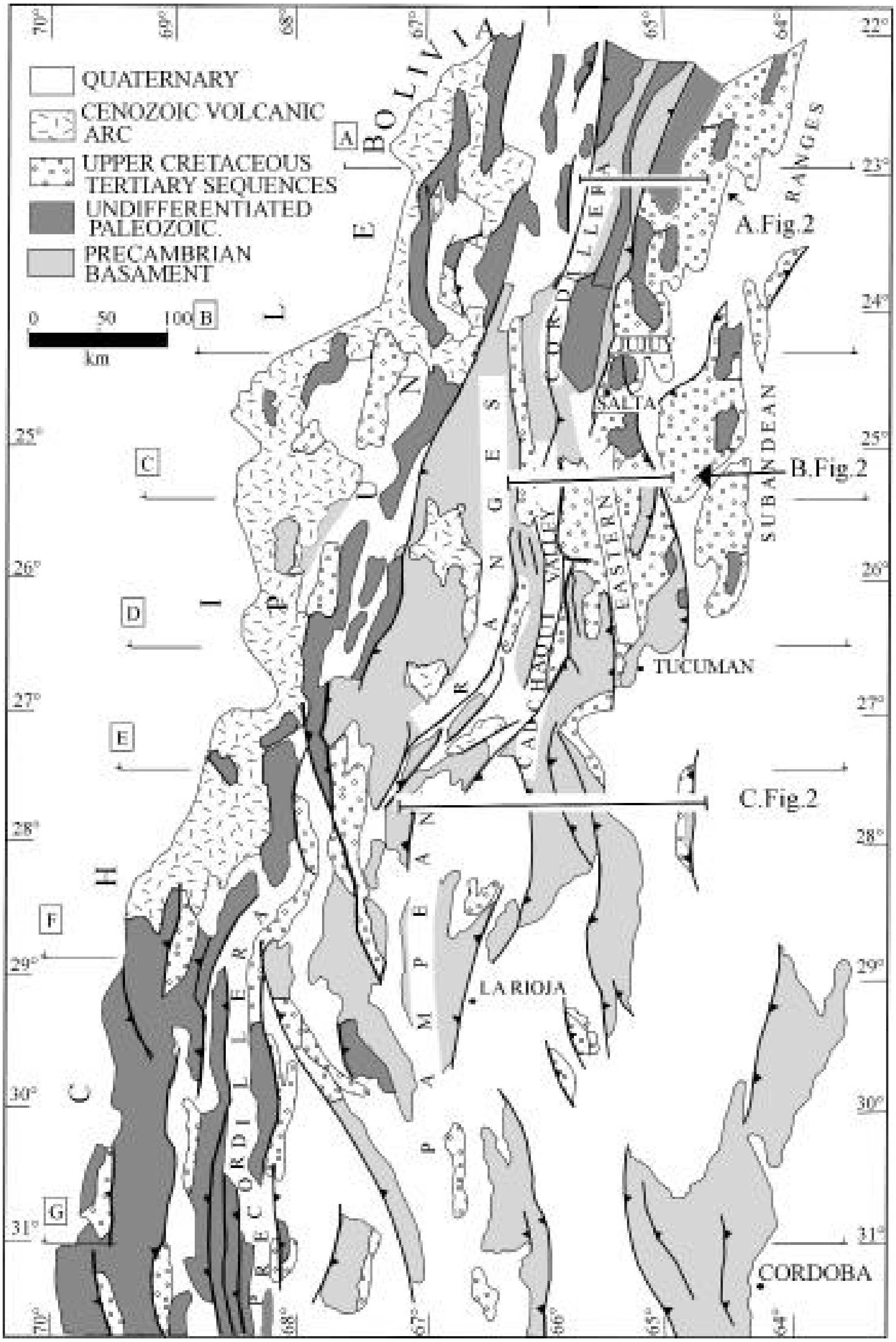
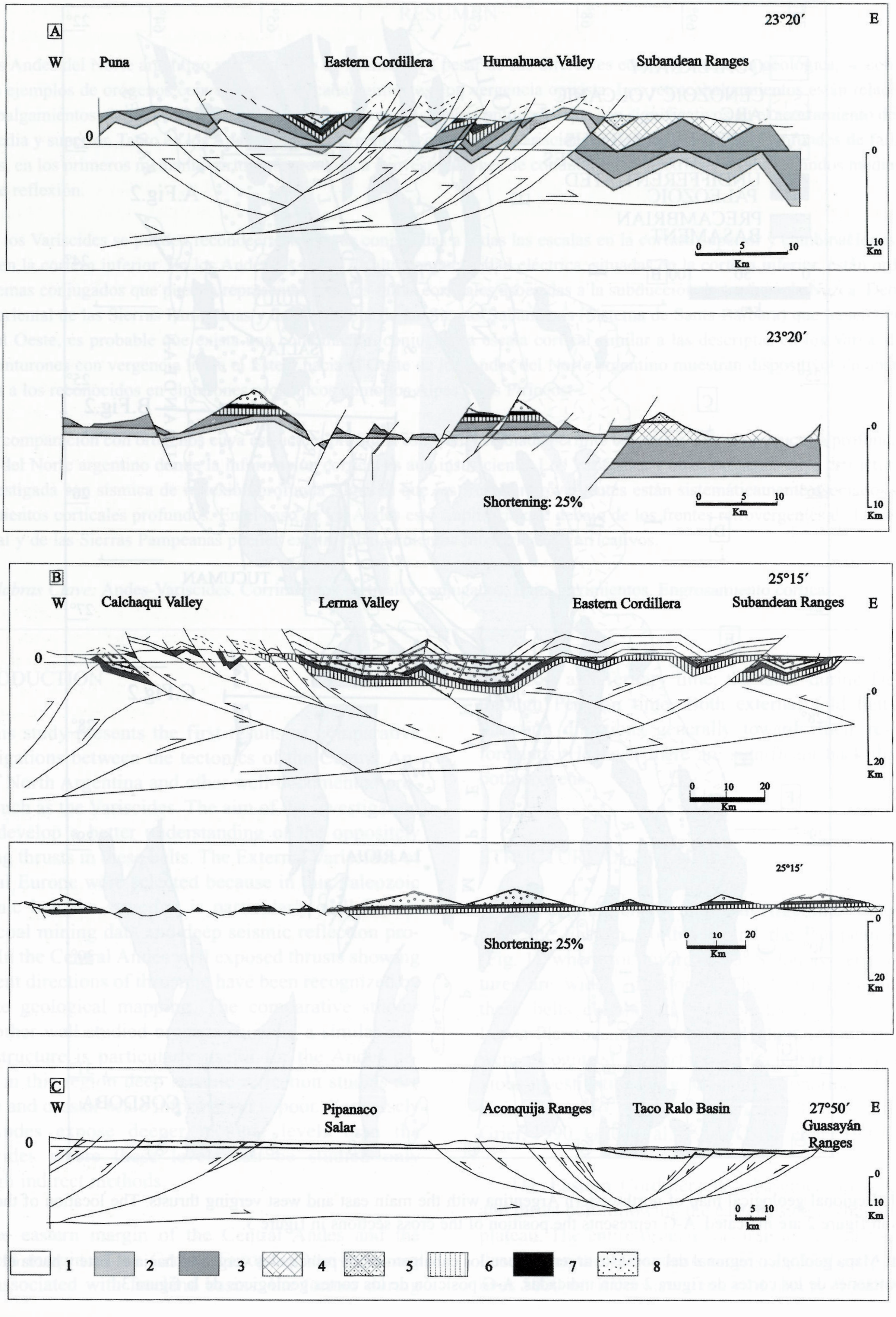


Figure 1. Regional geological map of northwestern Argentina with the main east and west verging thrusts. The location of the cross sections in figure 2 are indicated. A-G represents the position of the cross sections in figure 3.

Figura 1. Mapa geológico regional del noroeste argentino con los cabalgamientos principales vergentes hacia el Este y hacia el Oeste. Las ubicaciones de los cortes de figura 2 están indicadas. A-G posición de los cortes geológicos de la figura 3.


A
23°20′
W
Puna
Eastern Cordillera
Humahuaca Valley
Subandean Ranges
E
0
0 5 10 Km
0 10 Km
23°20′
Shortening: 25%
0 5 10 Km
0 10 Km
B
25°15′
W
Calchaqui Valley
Lerma Valley
Eastern Cordillera
Subandean Ranges
E
0
0 20 Km
0 10 20 Km
25°15′
Shortening: 25%
0 10 20 Km
0 20 Km
C
W
Pipanaco Salar
Aconquija Ranges
Taco Ralo Basin
27°50′
E
Guasayán Ranges
0
0 10 Km
0 5 10 km
1
2
3
4
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6
7
8

cambrian and Lower Paleozoic basement thrust over Cretaceous, Neogene and Pleistocene successions. The stratigraphy of its sedimentary cover has marked along-strike differences because the Eastern Cordillera is a Pliocene- Pleistocene orogenic belt intersecting obliquely older sedimentary basins. North of 25º S lat., it contains thick (Turner, 1970) Cambrian and Ordovician strata (Fig. 2 A). Between 25º and 26º S lat., the Paleozoic successions are replaced by Cretaceous-Tertiary continental rocks (Salfity, 1982) that have a combined thickness greater than 4000 m (Fig. 2 B). The Tertiary deposits lie on Precambrian basement south of 26º S lat., due to the absence of Mesozoic and Paleozoic rocks.

The eastern bounding thrusts of the Eastern Cordillera between 22º and 26º 30' S lat., are probably linked in the subsurface forming a major detachment. The displacement of these thrusts is as much as 15 km.

Between 24º and 26º S lat., the west-verging zone is separated from the east-verging one by a topographic depression coinciding with the Lerma valley (Fig. 2 B). The faults of the western edge thrust basement blocks over the Tertiary sequences which fill the tectonic depression of the Calchaquí valley (Fig. 3).

North of 23º 30' S lat., the Puna and the Eastern Cordillera are formed by a big detached basement plate thrust over the Subandean ranges. The Eastern Cordillera represents the most deformed border of this plate. This structural situation is illustrated in the cross-section of Fig. 2 A,which shows a 20 km deep décollement surface, whith a ramp under the border between the Eastern Cordillera and Subandean Ranges. Below the Subandean Ranges the décollement is about 15 km deep. The 30 km shortening along this cross-section represents the 25% of the original length. In the intermontane depression of Humahuaca (Fig. 2A) located on this plate the east-verging thrusts brought basement and Cretaceous rocks over the Pleistocene fanglomerates formed by material eroded from the Eastern Cordillera, incorporating these materials into the faulted belt.

South of 24º S lat., there is a significant structural change. The basement of the Puna is no more thrust over the Eastern Cordillera but underthrust, like a wedge, below its western edge, jacking the mountains belonging to it. This under-thrusting generates the back-thrusting of the Eastern Cordillera western belt. This part of the Eastern Cordillera, showing vergence to the East and to the West (Fig. 2B), constitutes a basement plate of about 25 km thick, detached from its substratum. According to Vergani and Starck (1989) the décollement surface could coincide with the boundary between two basement units with different rheologic behaviour. The shortening along this section is about 60 km, which represents 25% (Fig. 2B), similar to the one registered in the northedrn section. This implies that the shortening due to the eastward thrusting in the first section is partially transferred to the back-thrusting in the second one, mantaining a uniform regional shortening.

The main décollement surface of this section is divided in two branches, one which thrust the Cordillera Oriental basement over the Subandean ranges, and the other one which underthrust a basement wedge below the Subandean ranges, generating an other back-thrusting front which determines a triangular zone similar to the one of the western border.

The Calchaquí valley forms a narrow elongated north-south tectonic depression lying along the eastern border of the Puna plateau (Fig. 1). From 24º to 26º S lat. it separates the Puna and the Cordillera Oriental and farther south it extends into the Pampean ranges. The valley is bounded by reverse faults. The vergence of the faults

Figure 2. Cross-sections of the Eastern Cordillera showing double verging thrusting. The westward backthrusting is related to major eastward underthrusting. This fault arrangement is similar to that of the Rhenohercynian zone. 1. Proterozoic basement. 2. Cambrian. 3. Ordovician. 4. Silurian-Devonian. 5. Permo-Carboniferous. 6. Cretaceous (Pirgua Subgroup). 7 Cretaceous (Balbuena Subgroup). 8. Cenozoic. From our own field and photogeological information, and after published geological maps of González Bonorino 1951; Méndez et al., 1979; Ruiz Huidobro, 1955; subsurface information of Lerma Valley after Vergani and Starck (1991). Cross-sections location in figure 1.

Figura 2. Cortes transversales de la Cordillera Oriental que muestran los cabalgamientos con vergencia opuesta. El retro-cabalgamiento hacia el Oeste está relacionado a un bajo - cabalgamiento mayor con vergencia hacia el Este. 1. Basamento proterozoico. 2. Cámbrico. 3. Ordovícico. 4. Silúrico-Devónico. 5. Permo-Carbonífero. 6. Cretácico (Subgrupo Pirgua). 7. Cretácico (Subgrupo Balbuena). 8. Cenozoico. Según información de campo y fotogeológica de los autores, mapas geológicos publicados de González Bonorino, 1951; Méndez et al., 1979; Ruiz Huidobro, 1955. Información de subsuelo del valle de Lerma según Vergani y Starck (1991). Ubicación de los cortes en la figura 1.

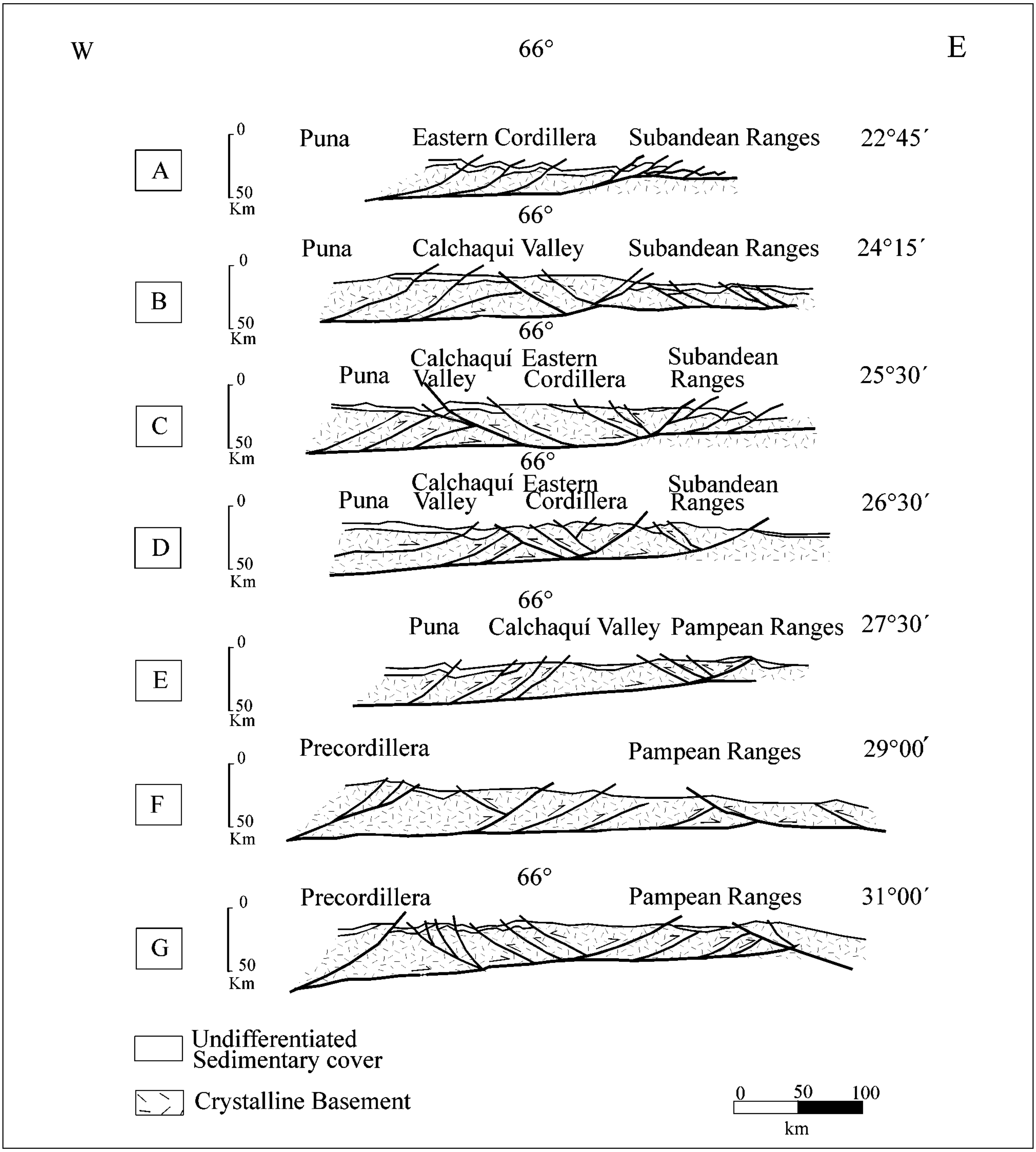

Figure 3. Schematic cross sections of the Andes of northwestern Argentina. Locations of the sections are in figure 1. The vertical scale is slightly exaggerated. From our own teledetection data -satellite images- and geological map of Argentina, scale 1: 2.500.000, Servicio Geológico Nacional (1982). Cross-section location in figure 1

Figura 3. Cortes transversales esquemáticos del noroeste de Argentina, su posición está en la Figura 1. La escala vertical está ligeramene exagerada. Según información de los autores obtenida por teledetección -imágenes satelitales- y Mapa Geológico de la República Argentina a escala 1:2.500.000, Servicio Geológico Nacional (1982). Ubicación de los cortes en la figura 1.

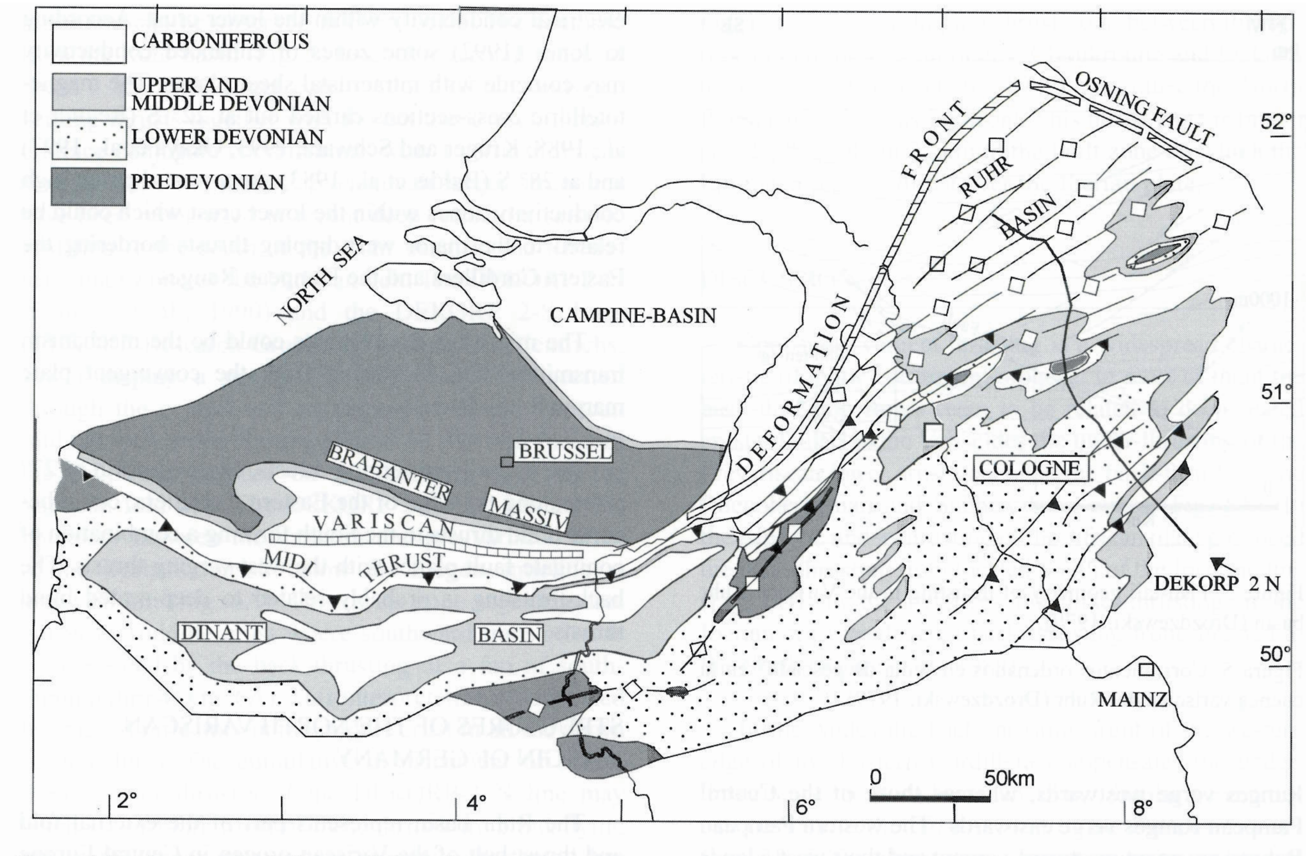

Figure 4. Regional geological map of Central Europe showing the main Variscan structural features (Drozdzewski, 1993).

Figura 4. Mapa geológico regional de Europa central con los principales rasgos de la estructura varíscica (Drozdzewski, 1993).

along each border is toward the axis of the depression. The edges of the Calchaquí valley are made up largely of Precambrian basement rocks. The valley is filled with folded non-marine Tertiary and Cretaceous rocks, occasionaly over 5000 m thick (Mingramm et al., 1979; Russo and Serraioto, 1978 ; Jordan and Alonso, 1987). It loses this character southward of 27º 30'S lat. but it is part of a much larger regional low, bounded by thrusts which continue without a major break to 34° S (Fig. 1). The backthrusting front of the eastern edge of the Calchaquí valley extends southward into the Pampean ranges for more than 1000 km. It represents a major structural element of the Andean foreland

At 27º S lat., the Andean foreland undergoes a pronounced change, the shortening is transferred completely to west-verging back-thrusts and the Subandean ranges are replaced southward by the suite of Precambrian basement blocks of the Sierras Pampeanas. On the eastern edge of the Pampean ranges there are no manifestations of eastward verging thrusts with the exception of the sierra Guasayán bounding fault. The whole assemblage of fault blocks of the eastern Pampean ranges is thrust westward, with its eastern edge unconformably covered by Tertiary non marine successions (Fig. 3E, F, G). It seems that all the shortening south of 27º S was brought about by underthrusting beneath the eastern border of the Andes. Considering the whole eastern Andean edge between 22º and 32º S lat. the backthrusting structures increase from north to south. South of 27º S lat., it is exclusively westward-vergent.

The Pampean Ranges consist of a group of crystalline basement block mountains (Fig. 3E, F, G), uplifted and tilted by bounding thrust faults (González Bonorino, 1950a; Jordan and Allmendinger, 1986; Urreiztieta, 1996). These mountains reach altitudes of more than 5000 m in their northern part, where they penetrate between the Puna and the Eastern Cordillera (Fig.1). Towards the south they are lower in height. The Pampean Ranges south of 27° S are physiographically separated from the main Andean chain. The blocks of the eastern Pampean

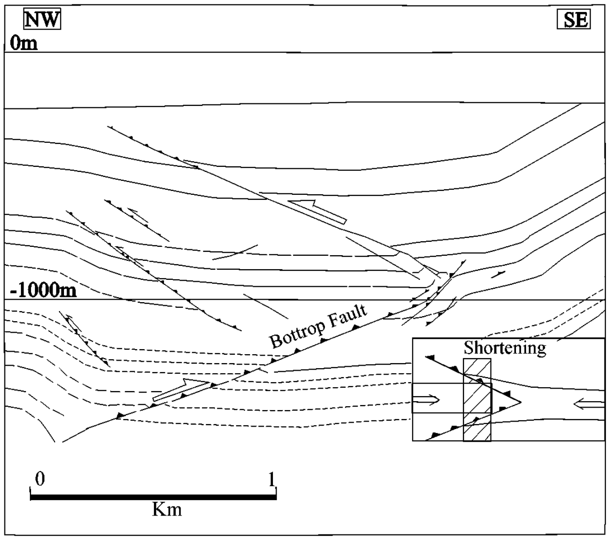

Figure 5. Fish-tail geometry of thrusting in the Variscan Ruhr basin (Drozdzewski, 1979).

Figura 5. Corrimientos ordenados en “cola de pescado” en la cuenca varíscica del Ruhr (Drozdzewski, 1979).

Ranges verge westwards, whereas those of the Central Pampean Ranges verge eastwards . The western Pampean Ranges are again westward-vergent and their west edge is marked by another back-thrusting front. These oppositely dipping thrust-faults generate big flat basement wedges detached from the mid crust. They produce geometries (Fig. 2C) following pop-up block models (Buttle, 1982) and triangle zones (Fig. 3).

Upper crustal shortening in the Pampean Ranges is negligible, being about 5% (Jordan and Allmendinger, 1986).

The deep structure of the Eastern Cordillera and the Pampean ranges is almost unknown, being based on interpretations using seismological data (Jordan and Allmendinger, 1986; Cahill et al., 1992), seismic refraction surveys (Schmitz et al., 1993), gravimetric data and magnetotelluric information (Krüger and Schwarz, 1993; Wigger et al., 1993).

After the studies of Grier (1990) and the seismological data of Cahill et al. (1992) a 25 km-deep detachment surface below the Eastern Cordillera is postulated. It could coincide with the main décollements of the Eastern Cordillera basement plates.

Magnetotelluric studies performed across different sections of the Andes show surfaces or zones of enhanced electrical conductivity within the lower crust. According to Jones (1992) some zones of enhanced conductivity may coincide with intracrustal shear planes. The magnetotelluric cross-sections carried out at 22° S (Reutter et al., 1988; Krüger and Schwarz, 1993, Okaya et al., 1997) and at 28° S (Baldis et al., 1983) show west-dipping high conductivity zones within the lower crust which could be related to the major west-dipping thrusts bordering the Eastern Cordillera and the Pampean Ranges.

The mid crust detachments could be the mechanism transmitting the shortening from the convergent plate margin in the Pacific.

The major East-verging thrusts, exposed north of 27° S lat. along the edge of the Eastern Cordillera, could become blind thrusts to the South forming a combination of conjugate fault planes with the west verging thrusts. The back-thrusting is probably related to deep-seated blind thrusts.

STRUCTURES OF THE NORTH VARISCAN MARGIN OF GERMANY

The Ruhr basin represents part of the external fold and thrust belt of the Variscan orogen in Central Europe (Fig. 4). Extensive mining has exposed molasse-type, coal-bearing clastic sequences of Late Carboniferous age with cumulative thicknesses up to 7 km (Drozdzewski, 1993). Surface outcrops and excellent three dimensional exposures by coal-mining activity have been systematically investigated (Drozdzewski et al., 1980, 1985; Kunz et al., 1988). Thus structural elements of the Variscan foredeep are well known. Reflection seismic investigations have added significantly to the knowledge of the structural style of the Ruhr basin.

Thrusting of the main faults of the Ruhr basin is directed mainly towards the foreland in the North. But many of these elements are accompanied by important oppositely dipping thrust faults. The northwest and southeast-vergent thrusts of the Ruhr basin form conjugate sets of shear planes. There are vertically arranged combinations of oppositely dipping thrusts (“fish-tail” structures, Drozdzewski, 1979), where displacement along each thrust falls to zero along the line of intersection of the two thrusts (Fig. 5). The kinematical effect of these fault combinations, in the ideal case of two similar scale faults, vertical thickening accomplished by shortening of bed-length without any definite direction of transport. These conjugate structures are widely recognized and can be observed at every scale. The example from the Ruhr basin (Fig. 5) reaches a vertical range of about 1 km. Still larger combinations of forelandward verging thrusts together with the antithetic back-thrusts produce conjugate combinations with a vertical dimension of some kilometers. Even much larger structures have been recognized in recent deep reflection seismic profiling to the south of the Ruhr basin in the Rhenohercynian Zone of the Variscan belt. The DEKORP 2-N (Franke et al., 1990) and the DEKORP 2-S lines (DEKORP Research Group, 1985, Behr and Heinrichs, 1987) display a nearly 500 km long cross-section through the central and northern part of the Variscan fold belt of Central Europe (Fig. 6 A). We will focus in the following account on the northern part of the Variscan fold belt. The DEKORP 2-N line reveals the boundary between the Variscan and pre-Variscan crust of the Brabant massif below the Siegen anticline at about 60 km (Fig. 6A). This thrust zone regularly dies out in the middle crust where southward translation is compensated by the back-thrusting of a fan of south-dipping thrust (Fig. 6A). This interpretation is supported by stacked reflectors in the middle crust in all the above seismic lines. The cumulative displacement of south-dipping back-thrustss of the DEKORP-2 N line may reach 10 - 15 km. Most of these thrusts are blind, dying out in the upper crust where orogenic shortening has been compensated by folding and uplifting. This explains why the oldest rocks of the Rhenohercynian zone occur in the Ebbe and Siegen anticlinoria, which are located above the conjugate structure in the lower and middle crust (Fig. 6A). In this model, levels above the conjugate structure have been uplifted by underthrusting from the South as well from the North. The kinematics during Variscan convergence has resulted in a coincidence of North and South dipping thrust zones (Oncken et al., 1999) . Other recent deep reflection seismic profiling has provided some additional instances of conjugate crustal-scale structures. Most impressive are seismic sections from the Swiss Alps (Fig. 6B) and the Pyrenees (Fig. 6C). The Swiss deep seismic investigations have revealed the nature of the controversial Insubric Line (a major orogen) parallel vertical fault zone extending throughout the entire chain (Heitzmann et al., 1991; Laubscher, 1991; Pfiffner et al., 1991). The figure 6B reveals the listric shape of the Insubric Line in depth indicating a north dipping thrust zone which is linked at a depth of 35 km with the south dipping Alpine suture zone. As a result of the oppositely dipping lithospheric-scale thrusting the African plate is forced into the European plate. The ECORS deep seismic reflection profiling of the Pyrenees (Fig. 6 C) provided a section that revealed the north dipping thrust zone between the European and the Iberian plates (Choukroune and ECORS team, 1989; Roure et al., 1989) generates the North Pyrenaen back-thrusting front. This thrust zone is linked at a depth of about 25 km to the fault zone on which the European plate is thrust over the Iberian plate.

DISCUSSION

Oppositely-vergent thrusting is a widespread characteristic of many convergent orogens. In most of them the back-thrusting fronts seem to be related to deep seated crustal faults. In the Variscides the under-thrusting of the Prevariscan lower crust generated the back-thrusts of the Rhenohercynian and Subhercynian zones (Fig. 6A). In the Alps the under-thrusting of the African plate produced the back-thrusting front located South of the Insubric line (Fig. 6B). In the Pyrenees the under-thrusting of the Iberian crust produced a back-thrusting front directed to the North (Roure et al., 1989).

In the Andes the back-thrusting front of the western edge of the Eastern Cordillera compensates the under-thrusting of the Puna basement plate. Similar geometries can be seen in the cross section of the Pampean ranges (Fig. 3E, F, G) where west vergent faults are related to eastward directed under-thrusting. This kind of structures were described too in another sections of the Andes (Baby et al., 1997; Dimieri, 1997)

In the oppositely-dipping thrusts the opposed shear directions are approximately synchronous. In the case of the Andes of North Argentina, the present day mountain belt is superposed on an older West-verging Paleozoic orogen (Ocloyic belt) and on an Upper Cretaceous rift-graben system, partially inverted by the Cenozoic Andean movements. Therefore it is probable that the West-verging branch of the conjugate fault system could be partially controlled by older Ocloyic faults (Mon, 1993) or by the inversion of the east dipping normal faults bordering the Upper Cretaceous grabens (Grier et al., 1992; Cahill et al., 1992).

Despite the fact that a comparison between the geometries of the upper crustal structure of the Andes with those of the deep crustal structure of other orogens could be considered as a method which is not absolutely rigorous, it seems the only one available to improve the hypothesis about the deep structure of the Andes, where most of the information consists of isolated geophysical data obtained by low resolution methods.

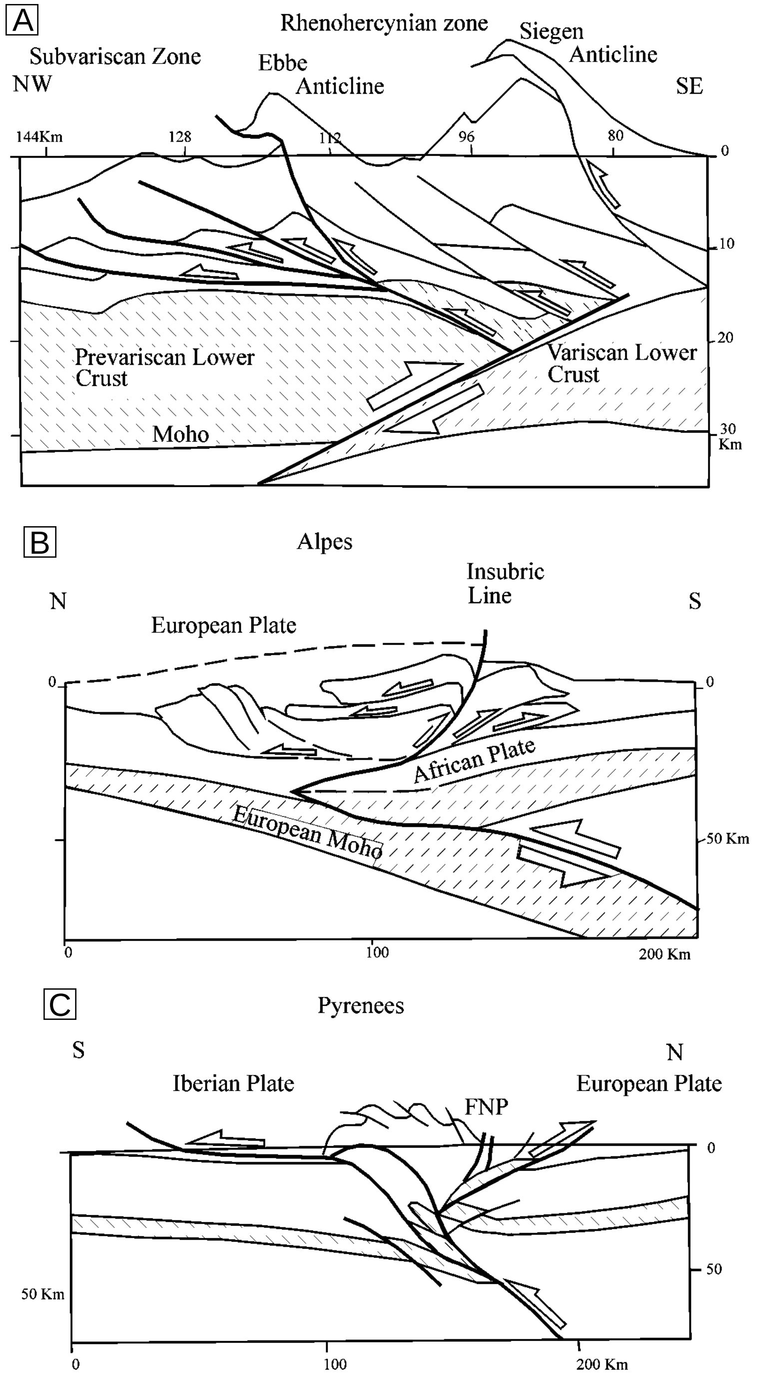

Figure 6. A) Simplified geological section across the northern part of the Rheno-hercynian zone. Several south dipping thrusts below the Siegen anticline were formed with the North dipping thrust zone of the lower crust, and an asymmetric conjugate structure (after Drozdzewski, in Francke et al., 1990). B) Interpretation of the main thrusts of the Alps (after Pfiffner et al., 1991). C) Interpretation of the deep structure of the Pyrenees (after Roure et al., 1989).

Figura 6. A) Corte geológico simplificado a través de la parte Norte de la zona Reno-hercínica. Muchos cabalgamientos con inclinación hacia el Sur por debajo del anticlinal de Siegen forman junto con la zona de cabalgamientos que inclinan hacia el Norte una estructura conjugada asimétrica (según Drozdzewski, in Francke et al., 1990). B) Interpretación de los principales cabalgamientos de los Alpes (Pfiffner et al., 1991). C) Interpretación de la estructura profunda de los Pirineos (Roure et al., 1989).

In the Pampean Ranges the structures affecting the crystalline basement are exposed at the surface, whereas in the Variscides they are only imaged by seismic investigations.

CONCLUSIONS

According to the examples of oppositely verging compressional orogens from the Variscides, Pyrenees and Alps in which crustal structure is known from deep seismic reflection surveys carried out in them, it seems that in every case the back-thrusting fronts are associated with deep thrusts cutting the lower crust. In the Andes subsurface data are of poorer quality but assuming that the back-thrusting fronts in the compressional belts are indicators of deep crustal thrusting and, that the Andes is unlikely to be an exception, it is possible to postulate significant lithospheric thrusting below the oppositely verging belts of the Andes. The West-verging thrust faults could be a consequence of deep seated East-verging thrusts beneath the eastern border of the Andes. In spite of the lack of enough data, if the Andean orogen has a similar deep structure as the Variscides or the Pyrenees, the back-thrusting front, following along the eastern border of the Calchaquí valley and the eastern Sierras Pampeanas for a total of nearly 1000 Km, may be the result of deep seated east-vergent blind thrusts.

AKNOWLEDGEMENTS

The investigations exposed in this paper have been carried out in the frame of the program of International Cooperation on Orogenic Belts (IPOB). The cooperation was initiated by the University of Tucumán, Argentina and the Geological Survey of Northrhine Westfalia at Krefeld, Germany, with the help of the Alexander von Humboldt Foundation (Germany) and the Research Council of Argentina (CONICET). The authors would like to acknowledge review and helpful comments of Rod Gayer, Henry Likorisch, Richard Allmendinger and two anonymous reviewers.

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