Trabajos de Geología, Universidad de Oviedo, 29 : 175-181 (2009)

Oviedo (Spain) 1-3 July 2008 International Meeting of Young Researchers in Structural Geology and Tectonics
ORSGET

The structure in the Bagneres de Luchon and Andorra cross sections (Axial Zone of the central Pyrenees)

P. Clariana[1*], J. García-Sansegundo[2] and J. Gavaldá[3]

[1]*Instituto Geológico y Minero de España, Madrid, Spain.*

[2]*Universidad de Oviedo, Oviedo, Spain.*

[3]*Conselh Generau d'Aran, Vielha, Lleida, Spain.*

[*]*e-mail: p.clariana@igme.es*

Abstract: Two vertical different structural domains have been recognized traditionally in the Axial zone of the Pyrenees: i) infrastructure: a deep seated domain with medium to high metamorphic grade and main flat-lying foliation and ii) suprastructure: a shallow domain with lower metamorphic grade and main steep foliation. Different and contradictory interpretations have been proposed to explain this structural zonation. The cross sections constructed have allowed us to observe the features of the transition zone between both domains in the central part of the Axial Zone and propose a new deformational sequence with which the structures of both domains are related.

Keywords: Pyrenees, Axial Zone, Variscan, thrusts.

This paper is based on two sections across the central part of the Axial Zone of the Pyrenees (Fig. 1). The first one, the Bagneres de Luchon cross-section, is located in the western part of the Garona Dome and the Lys-Caillaouas Massif (Figs. 2a and 3a) and the second one, the Andorra cross-section, runs from the eastern part of the Pallaresa Massif to the Llavorsí Syncline (Figs. 2b and 3b). The Pyrenees is an Alpine orogen, which resulted from the Euroasiatic and Iberian plates collision, from Upper Cretaceous to Miocene age. This collision caused the exhumation of the Paleozoic basement, which forms the Axial Zone nowadays, and where Variscan structures, one of them with Alpine reworking, are recognized. In the Variscan structure of the Pyrenean Axial Zone, for more than 50 years, a structural zonation has been recognized. It consists of two domains: "infrastructure" and "suprastructure", which are mainly distinguished by the attitude of the main foliation and the metamorphic grade (Zwart, 1963). In the "infrastructure" domain the main foliation has a flat-lying attitude and is usually associated with high temperature metamorphism. On the other hand, in the "suprastructure" domain the foliation is upright and was generated in low grade metamorphic conditions. The study of these two traverses, in the central part of the Axial Zone of the Pyrenees, allowed us to explain the transition between these domains through thrusts, which are developed in different structural levels. This interpretation of the Variscan structure of Pyrenean Axial Zone tries to provide a new structure arrangement, which is based on the structural relationships between the different zones. Moreover this interpretation brings into question some models previously presented by others authors.

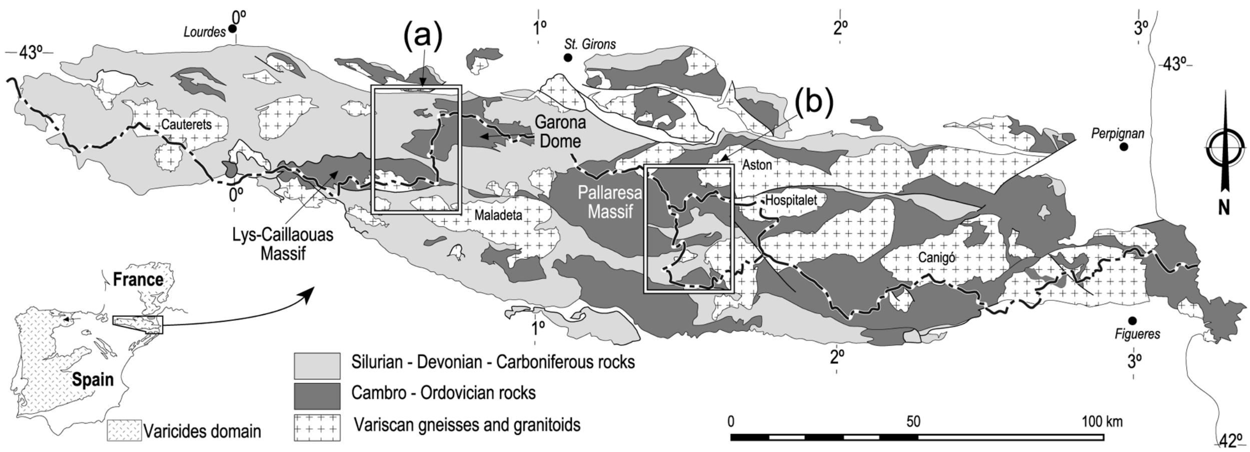

Figure 1. Variscides of Iberia and southern part of France, with location of the Pyrenean Axial Zone. Geological map of the Axial Zone of the Pyrenees, with location of the studied sectors.

Stratigraphy

Rocks outcropping in the studied sectors date from Cambro-Ordovician to Carboniferous. The main features of these rocks are summarized in different works in the last years (Barnolas and Chiron, 1996, amongst others). The Cambro-Ordovician succession consists of a monotonous alternation of quartzites and slates with some intercalations of limestones, quartzites or microconglomerates. Laumonier *et al.* (2004) have recently studied the Cambro-Ordovician stratigraphy using the stratigraphic section elaborated by Cavet (1957) in the eastern Pyrenees. These authors divide the pre-Caradoc successions of the central Pyrenees into two units: the Canaveilles Group, which is the oldest unit and the Joujols Group, mostly siliciclastic, where fossils are very rare. In the study area, the Canaveilles Group is absent and most part of the outcrops corresponds to portions of the Joujols Group. The Upper Ordovician, mainly siliclastic, lies unconformably over older units (García-Sansegundo *et al.*, 2004) and shows very different thickness from place to place. The Silurian is represented by black shales and limestone beds in the upper part. The Devonian rocks consist of series ranging from alternation of slates and limestone to predominantly slaty series. The Carboniferous shows limestones at the base and greywackes and slates (Culm facies).

Structure

The northern part of the Bagneres de Luchon geological cross-section (Fig. 3a), has been constructed using data from Zwart (1979), Kriegsman *et al.* (1989), García-Sansegundo (1996) and new fieldwork. In this area, Cambro-Ordovician rocks affected by flat-lying foliation are observed; they belong to the Garona Dome where the regional metamorphism can reach high grade conditions. The Devonian rocks show good development of upright folds with an associated steep foliation. The transition from the subhorizontal structures to the upright structures takes place in the Silurian black shales. Further to the south, in the Lys-Caillaouas Massif, the transition from zones dominated by subhorizontal structures, with medium to high grade regional metamorphism, to zones dominated by upright structures is a deep décollement level, which is located underneath the Upper Ordovician succession (Fig. 3a). Some of the thrusts related to this décollement level underwent reworking during the Alpine orogeny. Between the Garona Dome and The Lys-Caillaouas Massif a thrust with small displacement with an uplifted southern block is observed. Towards the western part of the Axial Zone of the Pyrenees, this thrust corresponds to the Gavarnie thrust, which causes a minimum amount of shortening of 15 km. Therefore, this Alpine fault must have been very important during the Mesozoic extension although its displacement was not totally balanced by the later compressive phase. Likewise, this thrust can be interpreted as a structure to developed before the Alpine cycle, although the Variscan décollement level must has not been the same than the Alpine décollement level, which would be located deeper (Fig. 3a) (ECORS Pyrenees team 1988).

The Andorra-Llavorsí geological cross section (Fig. 3b) has been constructed using data from Poblet (1991), Poblet *et al.* (1996), Clariana and García-Sansegundo (2009). The subhorizontal structures are dominant in the northern part: Aston Massif and eastern part of Pallaresa Massif to the south of Merens fault. In these zones the Variscan metamorphism can reach the migmatization. In the rest of this cross section, the main structures are upright or S-vergent folds with an associated steep foliation. The transition from the subhorizontal to upright structures takes place in a gradual manner. This can be observed to the south of Merens fault, where thrusts with associated upright folds are present (Fig. 3b). Like in the previous cross section, some of these thrusts were active during the Alpine cycle, although the deduced Variscan décollement level is nowadays located more superficial than the Alpine décollement level.

From the information provided by the cross sections in figure 3, plus detailed field observations, in the central part of the Axial Zone of the Pyrenees, three main deformation episodes are distinguished (García-Sansegundo, 1996; Clariana and García-Sansegundo, 2009):

D1 structures consist of a slaty cleavage (S1), only present in pre-Caradoc rocks. This foliation can be observed in the Garona Dome, Lys-Caillaouas and eastern Pallaresa massifs and Aston-Hospitalet domes. Folds associated with this cleavage have not been identified (García-Sansegundo, 1996; Clariana and García-Sansegundo, 2009).

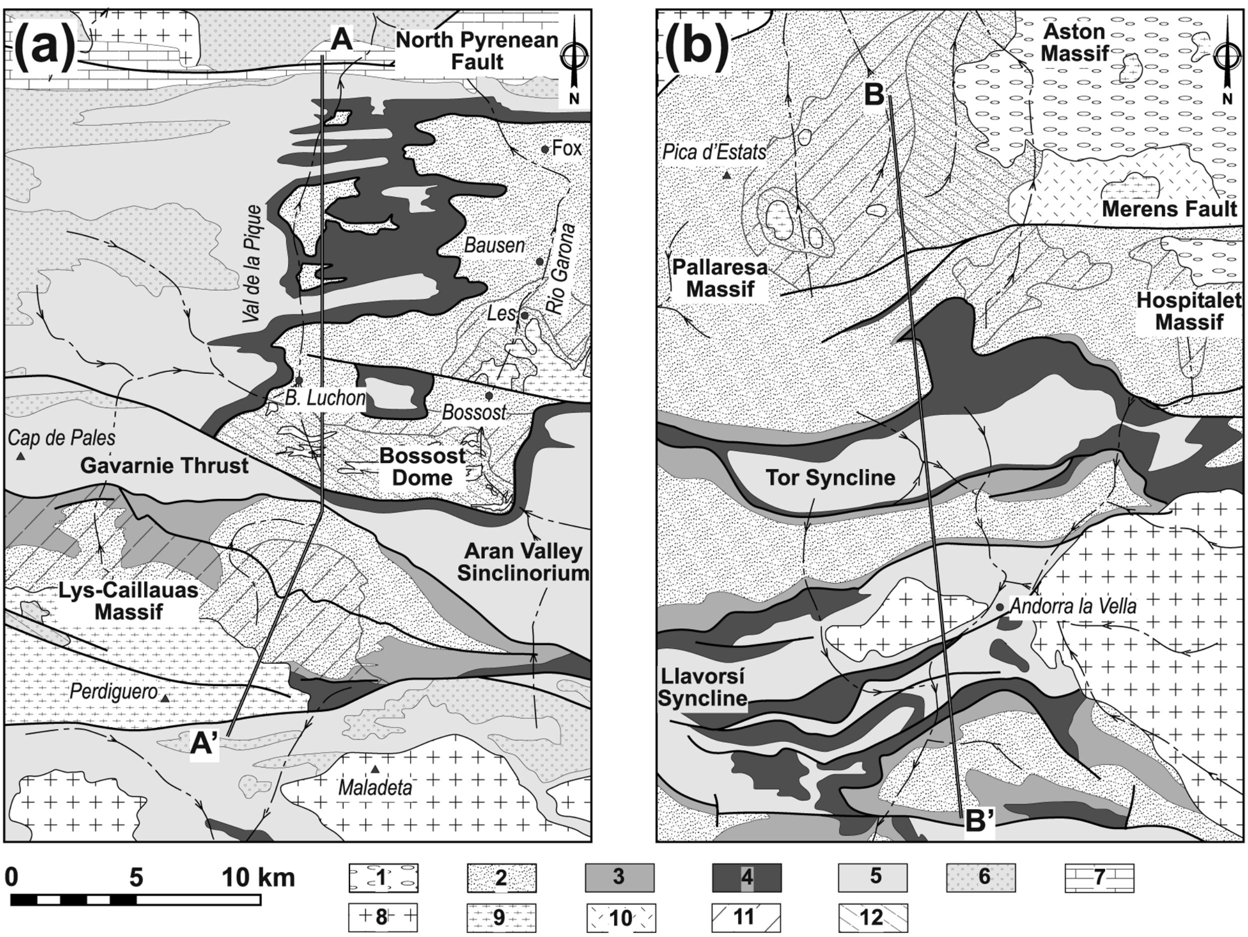

Figure 2. (a) Geological map of the western part of the Garona Dome and the Lys-Caillaouas Massif, (b) geological map of the eastern part of the Pallaresa Massif and the Tor and Llavorsí synclines. A-A' and B-B' are the geological cross-sections of figure 3. Legend: (1) Aston gneiss; (2) Cambro-Ordovician rocks; (3) Upper Ordovician rocks; (4) Silurian black shales; (5) Devonian slates and limestone; (6) Carboniferous rocks; (7) Mesozoic rocks; (8) Granodiorites; (9) Leucogranites, migmatites and pegmatites; (10) Migmatites; (11) Andalucite zone; (12) Sillimanite zone.

D2 structures are represented by a crenulation cleavage (S2) associated with E-W-trending, tight, recumbent and N-verging folds (Kriegsman *et al.*, 1989; García-Sansegundo, 1996; Clariana and García-Sansegundo, 2009). In levels located over the Cambro-Ordovician succession, the S2 foliation corresponds to a slaty cleavage, which is linked to E-W trending and N-verging folds. In the Garona Dome, western and central parts of the Lys-Caillaouas Massif, Aston-Hospitalet domes and southern part of the Merens fault, S2 is the main tectonic foliation (Fig. 3). D2 folds are developed at all scales and, usually, under low metamorphic grade conditions. Locally, close to granitic intrusions, high grade metamorphism conditions can be reached.

D3 structures are characterized by tight, E-W trending, upright folds developed at all scales, which are associated with a crenulation cleavage (S3). This tectonic foliation is developed in low metamorphic grade conditions and it is the dominant foliation in the Tor and Llavorsi synclines and in the southern and western parts of Pallaresa Massif. Upright and E-W trending faults and shear zones of similar orientation are included in this deformation episode, although some of these faults had an Alpine reworking.

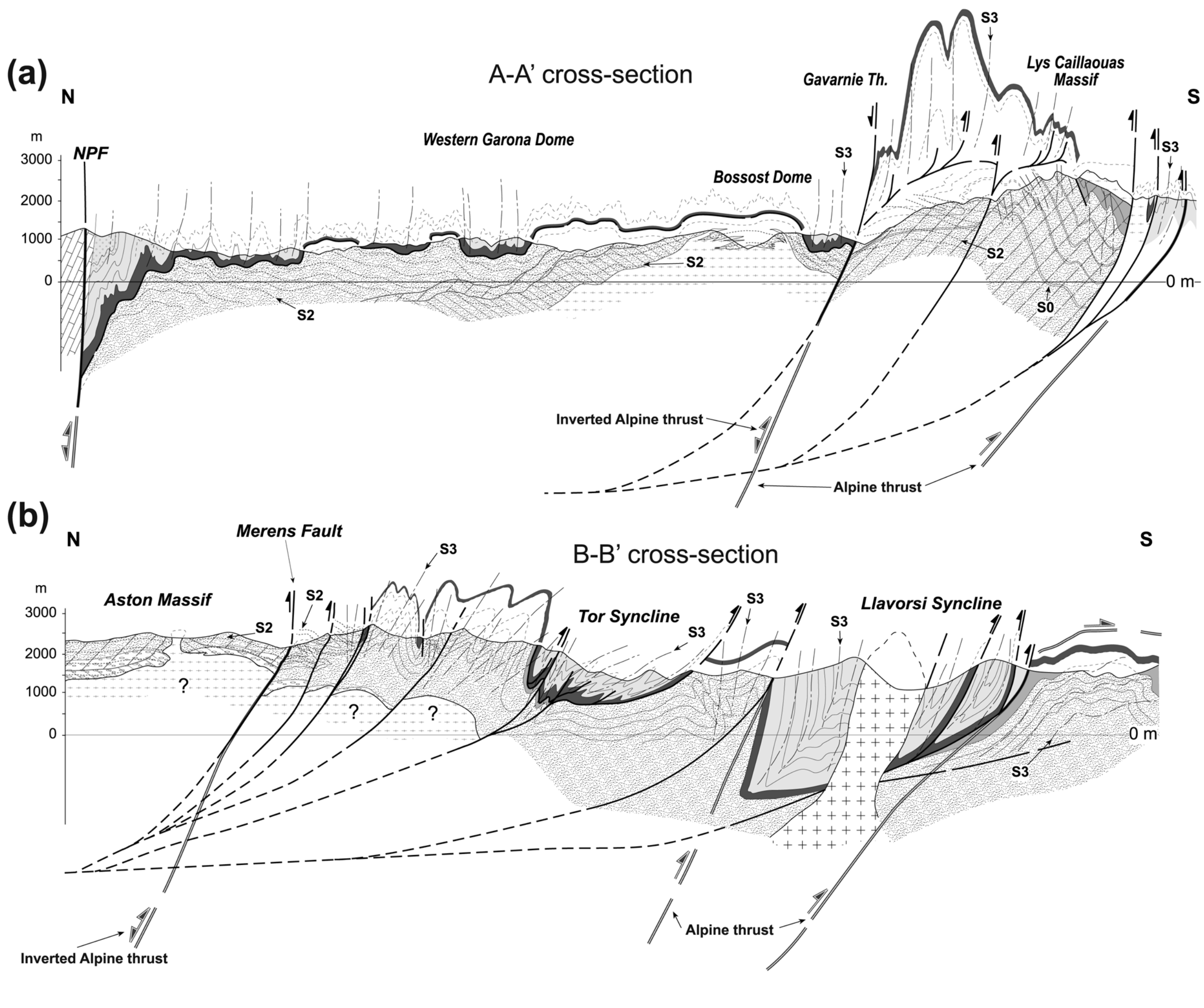

Figure 3. (a) Bagneres de Luchon geological cross-section. Location in figure 2, (b) Andorra geological cross-section. Location in figure 2. Same legend as in figure 2.

In the Garona Dome, the transition from D2 to D3 structures is sharp marked by the Ordovician-Silurian boundary (Fig. 3a). In the Silurian black shales, which are an excellent décollement level, many S-directed thrusts are observed. These thrusts are associated with folds that deform the S2 cleavage. Structurally upwards, these folds are better developed (fault-propagation folds) and have an associated foliation (S3) (Matte, 1969; García-Sansegundo, 1996). In the Tor Syncline, décollement levels in the Silurian shales are also observed, so that the D3 folds developed in Devonian rocks could have the same meaning than the folds developed in the Garona Dome (Fig. 3b). On the other hand, in the Cambro-Ordovician rocks located to the north of the Tor Syncline, upright and E-W trending faults have been observed linked to upright D3 folds with an associated axial planar foliation (S3). The relationship between faults and folds seems to show a common origin. In this respect, the existence of a deeper décollement level would be possible, which would be located in the Cambro-Ordovician succession. Likewise, in the eastern part of the Lys-Caillaouas Massif, D3 structures are well developed over a décollement level located below the Upper Ordovician succession. Within this décollement level, upright folds with an associated axial planar foliation S3 and small faults are present. Both D3 folds and faults frequently show associated Zn-Pb mineralizations.

Discussion

In the light of the observations showed in this paper, the S2 foliation is the dominant one in the "infrastructure" domain proposed by Zwart (1963), whereas the S3 corresponds to the main cleavage of the "suprastructure". The areas where the "infrastructure" can be observed show a domic shape and their cores correspond to igneous intrusions, which give rise to thermal metamorphism (HT-LP). This metamorphism has been related to the development of S2 (Guitard, 1970; Zwart, 1979; Van Eeckouth, 1986; Soula *et al.*, 1986; Kriegsman *et al.*, 1989) and interpreted in different ways. A synthesis of these interpretations is given below:

Soula (1982) and Soula *et al.* (1986) considered that the main foliations, S2 and S3 in this paper, have a coeval development. In their model the gentle or steep attitudes are related to diapirism associated with granitic and magmatic domes.

Geologists of the Leiden and Utrecht universities consider that our S2 cleavage occurred later than the S3 foliation, and the S2 would be associated with an extensional collapse in the last events of the Variscan Orogeny coinciding with or before the metamorphic peak (Van den Eeckhout, 1986; Van den Eeckhout and Zwart, 1988; Kriegsman *et al.*, 1989; Vissers, 1992; Aerden, 1994).

In line with the chronological relation proposed in this paper for the different Variscan structures, several authors suggested that both S2 and S3 cleavages are related to a compressional tectonic setting (Matte, 1969; Seguret and Proust, 1968 a and b; Matte and Mattauer, 1987; Carreras and Capellá, 1994; García-Sansegundo, 1996; Clariana and García-Sansegundo, 2009).

In this paper, we proved that the S2 foliation developed in earlier deformation stages than S3 cleavage. Although it would be possible to interpret that in the last stages of the D2 episode, at the same time as the intrusion of igneous rock, S2, previously generated under greenschist conditions, could have undergone flattening with development of porphydoblasts which grew under high temperature and low to medium pressure metamorphism conditions. According to this interpretation, in the Garona Dome, Mezger and Passchier (2003) link this HT metamorphism related to an extension event to the early granitic intrusions, later than the developement of S2 (in this paper) and before D3 structures.

Conclusions

Three main deformation events have been recognized in the central part of the Axial Zone of the Pyrenees. D1: slaty cleavage (S1) only developed in the Cambro-Ordovician sucession. D2: recumbent and N-verging folds with an associated foliation called S2. D3: E-W trending, upright folds with an axial planar cleavage (S3), which is the main foliation in the southern part of the study area.

Only in the Bossots, Lys-Caillaouas and Astón-Hospitalet domes high grade metamorphism conditions were reached. This high grade metamorphism can be explained in relation with granitic intrusions at the end of D2 episode, under extensional regime conditions. The intrusion of granitic bodies could have produced flattening of S2, previously generated in low grade metamorphism conditions, and could give rise to sintectonic growth of high and medium grade metamorphic minerals.

The transition between structural domains proposed by Zwart (1963): "infrastructure" and "suprastructure", can be related to thrusts, associated with D3 folds, and developed in different structural levels. These structural levels are located in: 1) Garona Dome: in the Silurian shales, 2) Lys-Caillaouas Massif: below the Upper Ordovician succession, and 3) Eastern Pallaresa Massif: in the lower part of the Cambro-Ordovician succession.

Acknowledgements

This work is a contribution of the DGCYT (General Direction of Science and Technology of the Spain Ministry of Education and Science) project CGL2006-08822/BTE and the Consolider-Ingenio 2010 Programme, under project CSD2006-0041, "Topo-Iberia". Partial financial support was provided by the Instituto Geológico y Minero de España (IGME) and the Centre d'Estudis de la Neu i de la Muntanya d'Andorra (CENMA).

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