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Thrust sequences in the eastern Spanish Pyrenees

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Abstract—Detailed mapping of the South Pyrenean zone in the eastern Spanish Pyrenees shows that a great number of Alpine thrusts affect the basement and the cover. The geometry of the thrust structures and their propagation sequence can be interpreted from balanced sections. The folding dies out downwards, from the higher thrust sheets to the lower ones and demonstrates a piggy-back thrusting sequence. These thrusts form a duplex. The sole thrust of this duplex is the Vallfogona thrust. The roof thrust is rooted somewhere within the Axial Zone. The thrusts climb southwards from the Axial Zone basement up into Tertiary cover sediments. These thrusts have been folded so that they now dip to the south and form the southern side of the Axial Zone antiformal stack. Locally, smaller antiformal stacks developed and produced strong folds in the higher thrust sheets. The South Pyrenean zone studied is equivalent to the Gavarnie nappe and the connection between them, below the detached South Pyrenean Central unit, may be the Nogueres zone.

INTRODUCTION

WE HAVE studied the South Pyrenean zone of the Eastern Pyrenees to the east of the Pedraforca nappe with special emphasis on the sector between the rivers Freser and Ter (Fig. 1). The aim of our paper is to show the geometry of the thrusts in this area and establish the thrusting sequence. The implications in the structure of the Pyrenees are also discussed. To achieve the above we have mapped the area and we have drawn several cross-sections, some of them balanced (Dahlstrom 1969).

The lithostratigraphy of the studied area is characterized by the almost complete absence of the Mesozoic rocks in the cover sequence. The pre-Hercynian basement is unconformably overlain by a Stephano-Permian red bed sequence which is sometimes completely volcanic. The Uppermost Cretaceous–Lowermost Paleocene continental deposits, called Garumnian facies, overlie the Stephano-Permian sequence in the west of the studied area and directly overlie the basement rocks in the east. Above the Garumnian beds are a thick Eocene sequence. The basement rocks (ranging in age from the Cambro-Ordovician to the Lower Carboniferous) consist of several structural units bounded by Alpine thrusts (Muñoz & Sabat 1982).

STRUCTURE

In the studied area a great number of Alpine thrusts affect the basement and the cover (Muñoz *et al.* 1983). These thrusts are specially visible in the Stephano-Permian and Garumnian beds where they produce a great number of repetitions. They also cause the repetition of the pre-Hercynian rocks over the cover sediments.

Structural units

The basement and cover rocks form several thrust sheets which have been grouped in two main structural units: Cadí nappe and Lower thrust sheets (Fig. 1). These structural units are described from the top of the structural succession downwards.

The Cadí nappe (Puigdefabregas & Soler 1980) is the highest structural unit consisting of a Devonian and Lower Carboniferous basement overlain by a thick series of Stephano-Permian red beds followed by Garumnian and Eocene sediments (Fig. 2). The floor thrust of the Cadí nappe, called the Serra Cavallera thrust, is located in the weak black Silurian shales and climbs up section southwards to the marls of the Lower Eocene.

The Lower thrust sheets, which lie below the Serra Cavallera thrust, are formed of several units of Cambro-Ordovician and Upper Ordovician rocks with a Garumnian cover. These have been named the Bruguera, Campelles, Ribes de Freser and Ribes–Camprodon thrust sheets (Figs. 1–2). However most of the area is occupied by the Ribes–Camprodon thrust sheet (formed of Cambro-Ordovician and Upper Ordovician rocks northwards of the Ribes–Camprodon thrust). The other thrust sheets are only present in the Freser valley and in the Rocabruna area, underlying the Cadí nappe (Fig. 1).

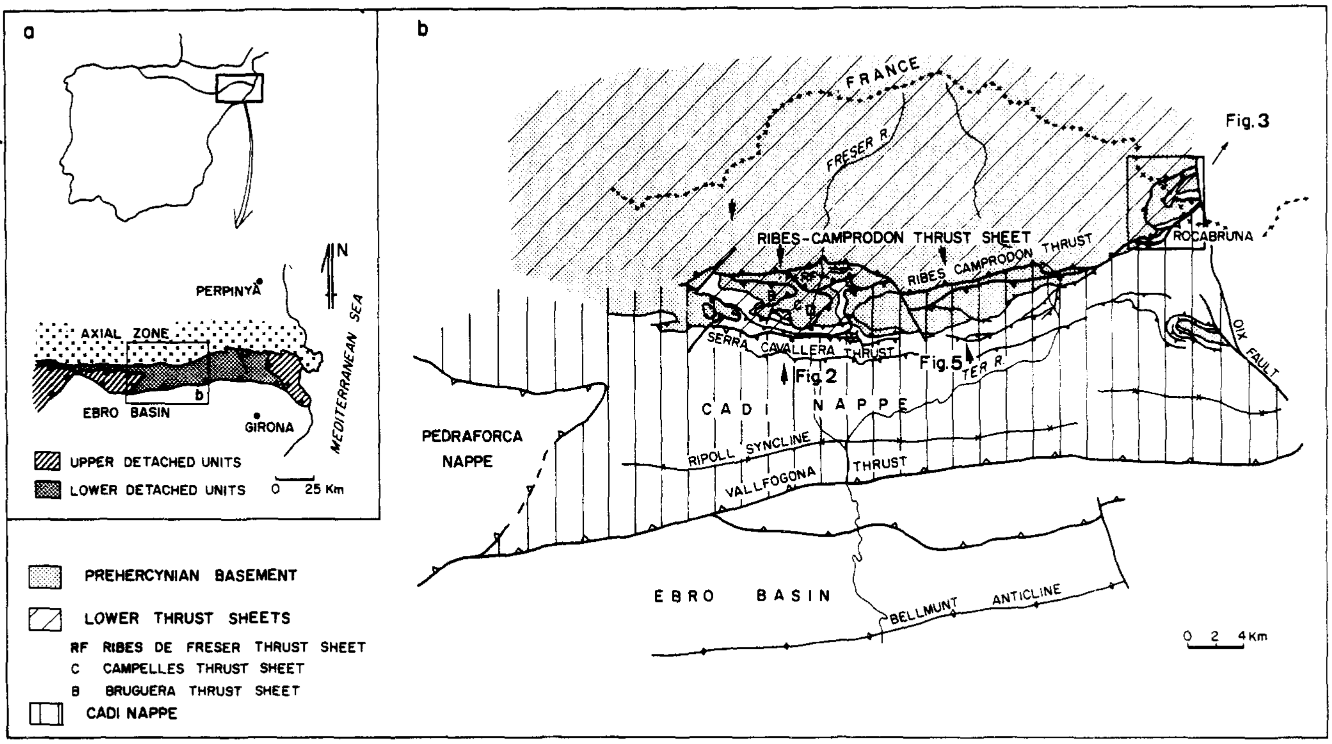

Fig. 1. (a) Location map of the studied area. (b) Structural map between the Llobregat river and the Oix fault showing the structural units and the main thrusts and folds. Location of the other figures.

In the Freser Valley we can observe three distinct thrust sheets (Fig. 2). The higher one, called the Bruguera thrust sheet, consists of a pre-Hercynian flyschoid series of unknown age, supporting a Stephano-Permian volcanic sequence and Garumnian beds. The Campelles thrust sheet, underlying the Bruguera thrust sheet, consists of Upper Ordovician limestones and carbonate shales overthrusting the lower Ribes de Freser thrust sheet of Upper Ordovician volcanic rocks. The Garumnian beds in the Freser river tectonic window would represent the cover of the two lower thrust sheets.

In the Rocabruna area, a duplex has developed below the Cadí nappe. This nappe is represented in this zone by Garumnian limestones and by an Eocene sequence (Fig. 3). The Rocabruna duplex consists of small horses of Ordovician, Silurian and Garumnian rocks. A thrust sheet formed by Cambro-Ordovician rocks and Garumnian beds underlies the Rocabruna duplex and overthrusts the Garumnian cover of a lower thrust sheet. These latter Garumnian beds outcrop in a tectonic window below the Cambro-Ordovician rocks (Fig. 3).

Description of the structures

In the studied South Pyrenean zone we can observe the following main structures from south to north (Fig. 4): (a) foreland E–W trending concentric folds, (b) a northward dipping thrust, called the Vallfogona thrust, (c) the Ripoll syncline, (d) southward dipping thrusts and (e) the northward-dipping Ribes–Camprodon thrust.

The foreland concentric folds imply the existence of a detachment level at depth that represents the continuation to the south of the Vallfogona thrust. The Vallfogona thrust becomes flat downwards and can be recognized in seismic sections. This thrust is of post-Bartonian age, and a change of facies can be observed in the Eocene sediments across the thrust. It is therefore difficult to restore this thrust to have a cut off at the same stratigraphic reference level in the hangingwall and in the footwall of the thrust. Only sedimentological considerations can be used to evaluate the displacement of the Vallfogona thrust. That is the reason why the pinline has been situated to the north of the balanced section (Fig. 4) in the Ribes–Camprodon thrust. To the south of the pinline southward-dipping thrusts affect the basement and the cover and the most important of these is the Serra Cavallera thrust (Fig. 2).

Minor thrusts are common within the Devonian and Lower Carboniferous basement. Sometimes some of these thrusts are quite important and separate Devonian thrust sheets that have different sequences of limestones. It is difficult to infer whether these thrusts are of Hercynian or late Hercynian age or whether they are Alpine. Some of them are clearly Alpine because they involve post-Hercynian rocks (Muñoz *et al.* 1983). On the other hand Hartevelt (1970), Santanach (1974) and Llac (1979) describe Hercynian and late-Hercynian thrusts to the west of the studied zone.

In the Freser Valley between two tear faults, a thrust climbs up section from the Serra Cavallera thrust and cuts off previously formed higher thrusts. This produces an anomalous superposition of the Devonian rocks over the Stephano-Permian and Garumnian beds (Fig. 2).

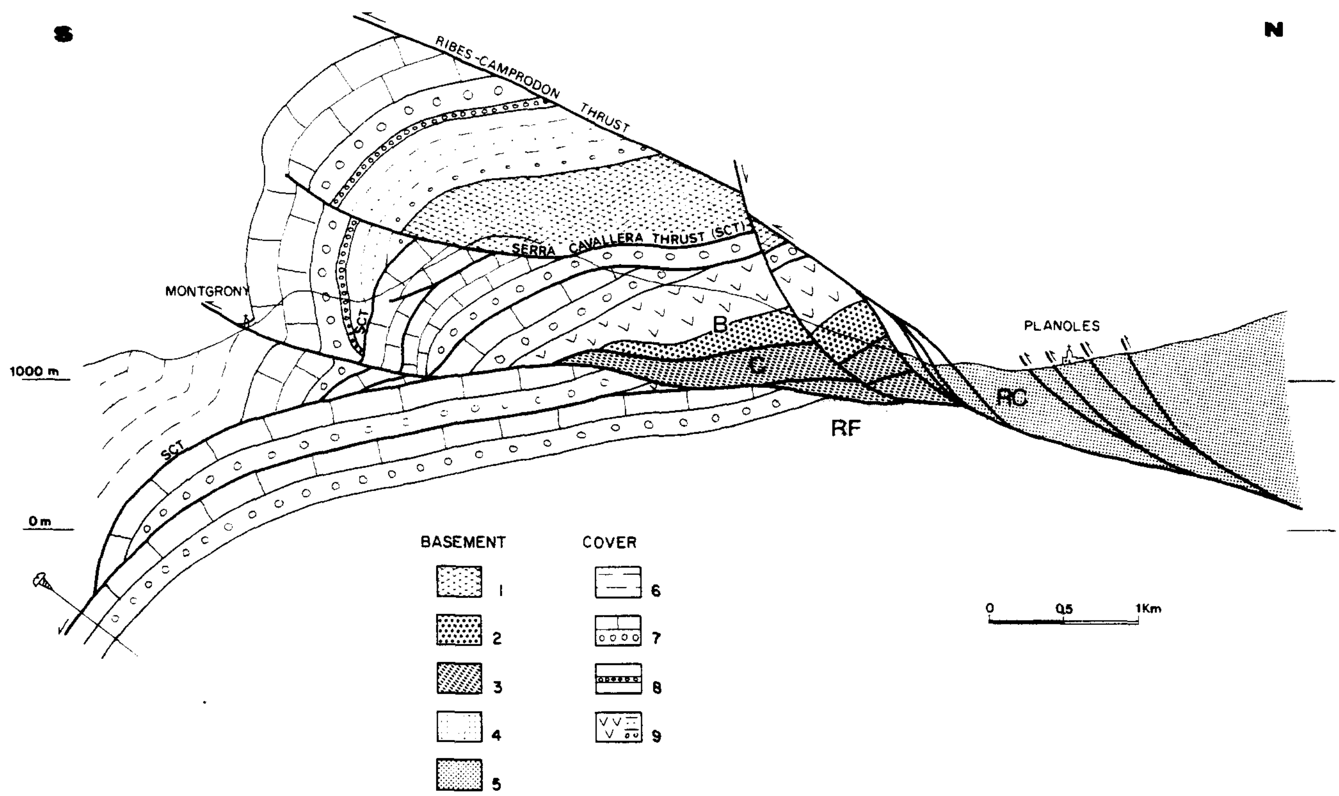

Fig. 2. Cross-section through the Freser antiformal stack. For location see Fig. 1(b). Key: (1), Silurian, Devonian and Lower Carboniferous (Cadí nappe); (2), Pre-Hercynian flyschoid series (Bruguera thrust sheet); (3), Carbonate Upper Ordovician (Campelles thrust sheet); (4), Volcanic Upper Ordovician (Ribes de Freser thrust sheet); (5), Cambro-Ordovician and Upper Ordovician (Ribes–Camprodon thrust sheet); (6), Eocene; (7), Garumnian; (8), Cretaceous; (9), Stephano-Permian; B, Bruguera thrust sheet; C, Campelles thrust sheet; RF, Ribes de Freser thrust sheet and RC, Ribes–Camprodon thrust sheet.

The thrust sheets are affected by E–W trending folds verging to the south, the lower thrust sheets being less folded than the higher ones (Fig. 2). These folds are related to the thrusting sequence development and their dying out downwards demonstrates a piggy-back thrusting sequence. A cleavage is also developed in the cover sediments. It is always almost at right-angles with the bedding, and it is also folded by the emplacement of the lower thrust sheets. This cleavage formed by layer-parallel shortening at the initial stages of the thrusting, before ramping of the thrusts.

The piggy-back thrusting of the Lower thrust sheets in the Freser Valley and Rocabruna produce antiformal stack duplexes (Boyer & Elliot 1982). These structures imply a large shortening of about 60 per cent deduced from the balanced sections, and the stratigraphic differences between the basement involved in the thrust sheets should be emphasized. In the higher thrust sheets of the antiformal stacks, thrusts are inverted. Between these antiformal stacks the thrusts dip constantly to the south (Fig. 5). The southward-dipping thrusts disappear to the south in the Lower Eocene sediments (Fig. 4). This can be interpreted in two ways: (i) the thrusts are cutting up section southwards and roofing in the Lower Eocene or (ii) the thrusts are unconformably overlapped by post-Cuisian sediments. All the southward-dipping thrusts and the antiformal stacks are cut to the north by the northward dipping Ribes–Camprodon thrust. The sections show the geometry of out-of-sequence thrusting and the significance of this thrust will be discussed later.

Structural interpretation

The structures of the studied area were interpreted by Vergely (Seguret & Vergely 1969, Vergely 1970) as a result of the superimposition of two deformation phases. During the first one subhorizontal thrusts with associated folds were formed. During the second one the structures of the first phase were folded by E–W trending folds and an axial-plane cleavage, dipping 45° northwards, was developed.

We suggest an alternative interpretation for the structural evolution, as follows. We consider that the disappearance of the southward-dipping thrusts to the south is due to their roofing in the Lower Eocene marls, having recently observed Lutetian gypsum involved in one of these thrusts. If we accept this idea, the studied South Pyrenean zone, below the Pedraforca nappe, represents a duplex formed by piggy-back thrusting. The Vallfogona thrust is the sole thrust of this duplex. The thrusting of the younger Lower thrust sheets below the Serra Cavallera thrust produced antiformal-stack duplexes. The Ripoll syncline is situated between the northward-dipping Vallfogona thrust and the southward-dipping thrusts roofed at the top of the Garumnian beds. The thrusts climb up

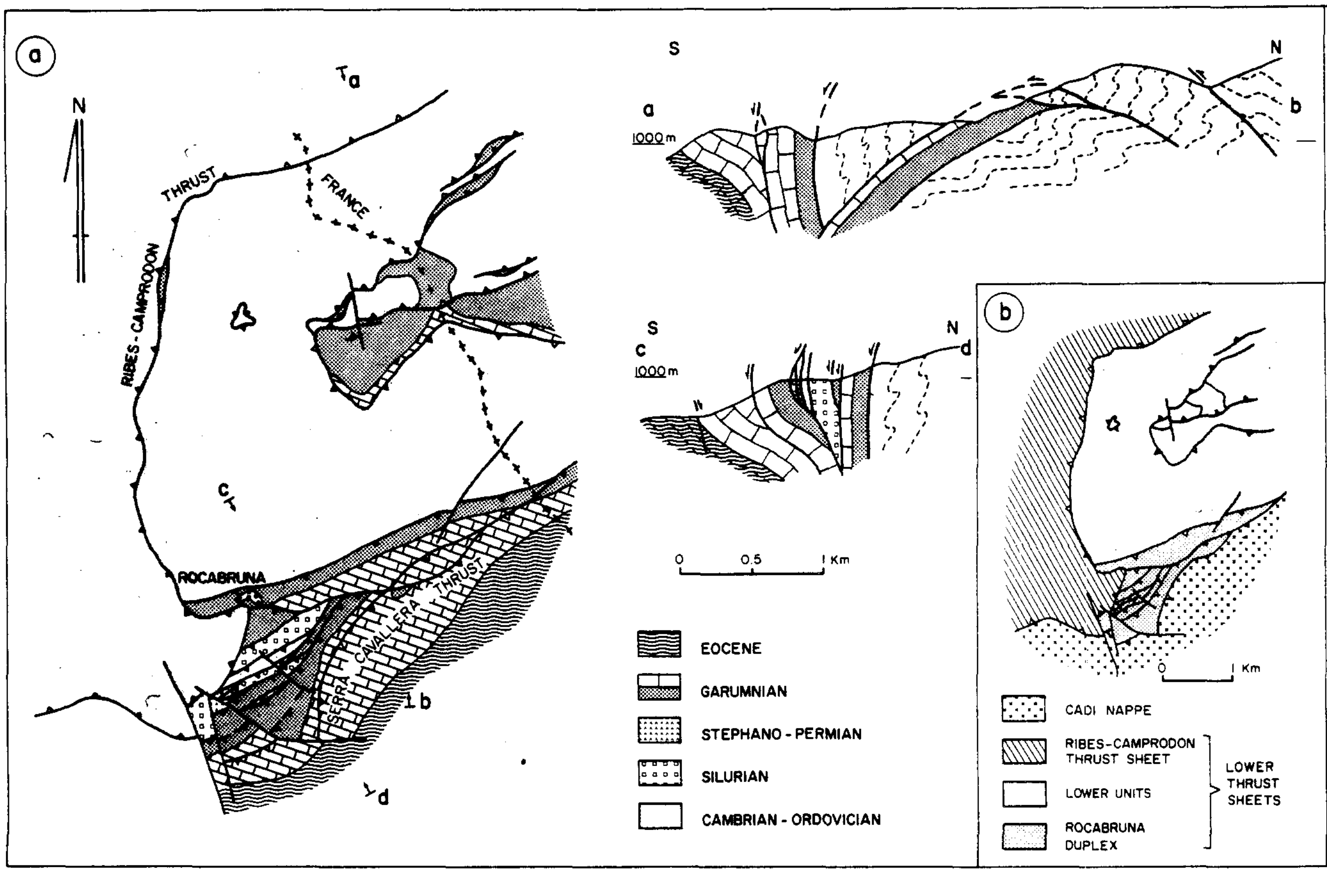

Fig. 3. (a) Detailed geological map of the Rocabruna culmination. Sections showing the structure of the Rocabruna culmination (see location in the map). (b) Structural units in the Rocabruna area.

section southwards from the basement to the Eocene sediments. The higher and older thrusts are progressively folded by the development of lower and younger thrusts.

The lower thrusts climb up section and may truncate the previously folded higher thrusts. This fact would explain the out-of-sequence geometry of the Ribes–Camprodon thrust. It should be emphasized that this thrust constitutes an important structural feature in the studied area. In the field it is revealed by small slices of younger rocks (pre- and post-Hercynian rocks) situated between older rocks (mainly Cambro-Ordovician), giving rise occasionally to fault gouges tens of meters thick. The Ribes–Camprodon thrust can be interpreted as an out-of-sequence thrust cutting all the horses of the antiformal stacks. According to this hypothesis, it initially climbed up from below the Ribes de Freser thrust sheet (in the Freser Valley) and the trailing edge of the antiformal stack was originally above the present surface. A second interpretation of the above-mentioned thrust is that of an out-of-sequence thrust developed by the unsticking and movement of the roof thrust of the antiformal stacks. In both cases the Ribes–Camprodon thrust represents the last stage in the development of a complex antiformal stack whose floor thrust is stuck, producing renewed deformation hindwards of the sticking point.

DISCUSSION

From the proposed structural evolution, some features of the structure of the Pyrenees should be taken into account in a global interpretation of the Pyrenean chain. The most important of these is the similarity between the South Pyrenean zone studied here and the Gavarnie nappe (Parish 1984), and the important crustal shortening in both cases (Fig. 6).

The Cadí nappe has been considered by most geologists, specially since Seguret's work (Seguret 1972), as an autochthonous or parautochthonous unit in continuity with the southern foreland. From the balanced cross-section (Fig. 4) and the proposed structural evolution, a minimum displacement of about 15 km for the Cadí nappe is evaluated, apart from the displacement due to the Vallfogona thrust.

The Cadí and Gavarnie nappes, relatively parautochthonous to the detached central south Pyrenean unit, have equivalent sedimentary characteristics (absence of Jurassic and Lower Cretaceous sediments and Eocene flysch) and similar basement involvement in the thrusting. This suggests that the Gavarnie nappe and the Cadí nappe represent an homologous structural unit.

The Serra Cavallera thrust would be equivalent to the Gavarnie thrust. The Lower Paleozoic rocks cropping out inside the Gavarnie tectonic window would represent the Lower thrust sheets unit. In the studied area this

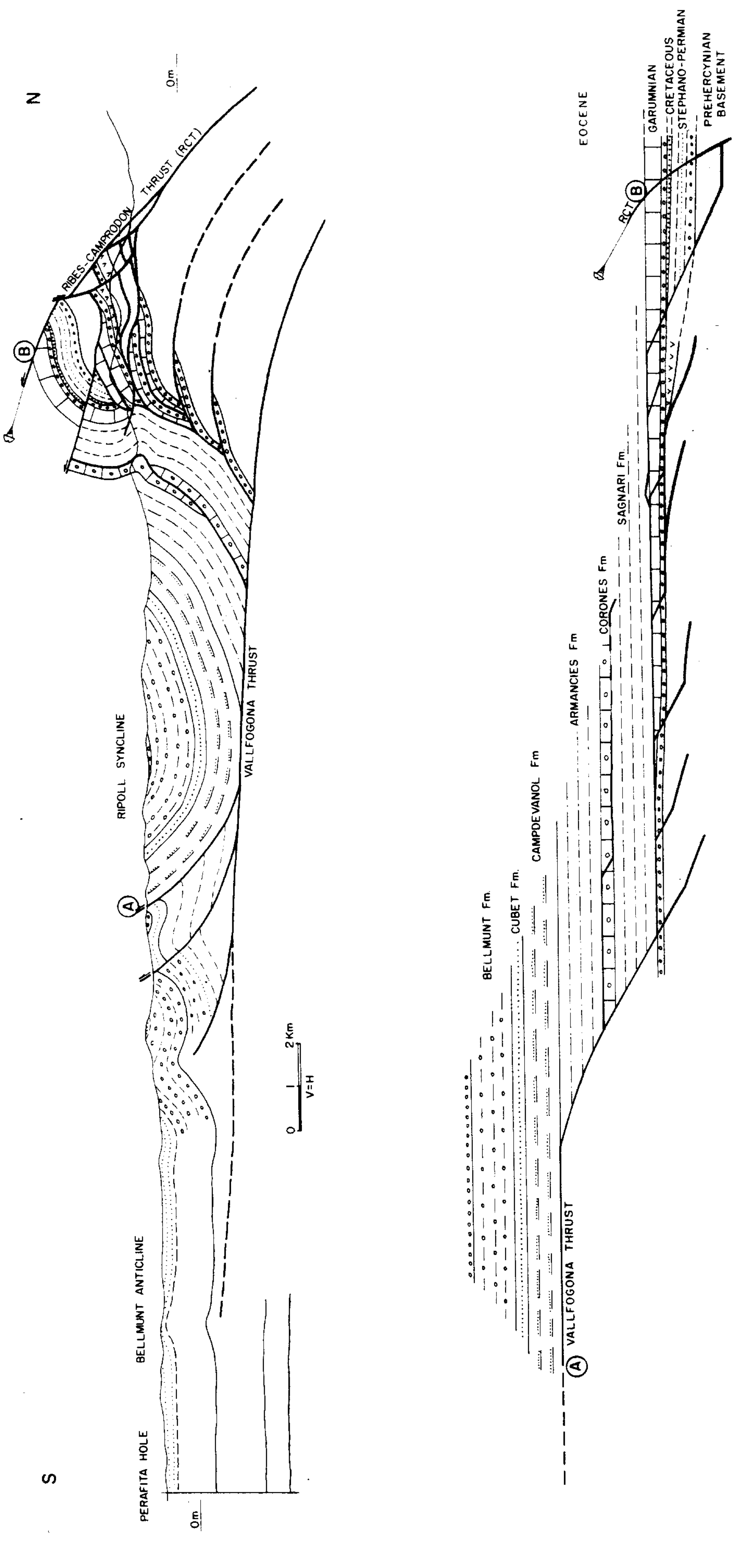

Fig. 4. Cross-section through the studied South Pyrenean Zone. Lower section shows balanced section A–B on the upper cross-section. The Vallfogona thrust is not restored (see text for explanation). The change of ornament south of point A in the upper section is due to a facies change of the Eocene Sediments.

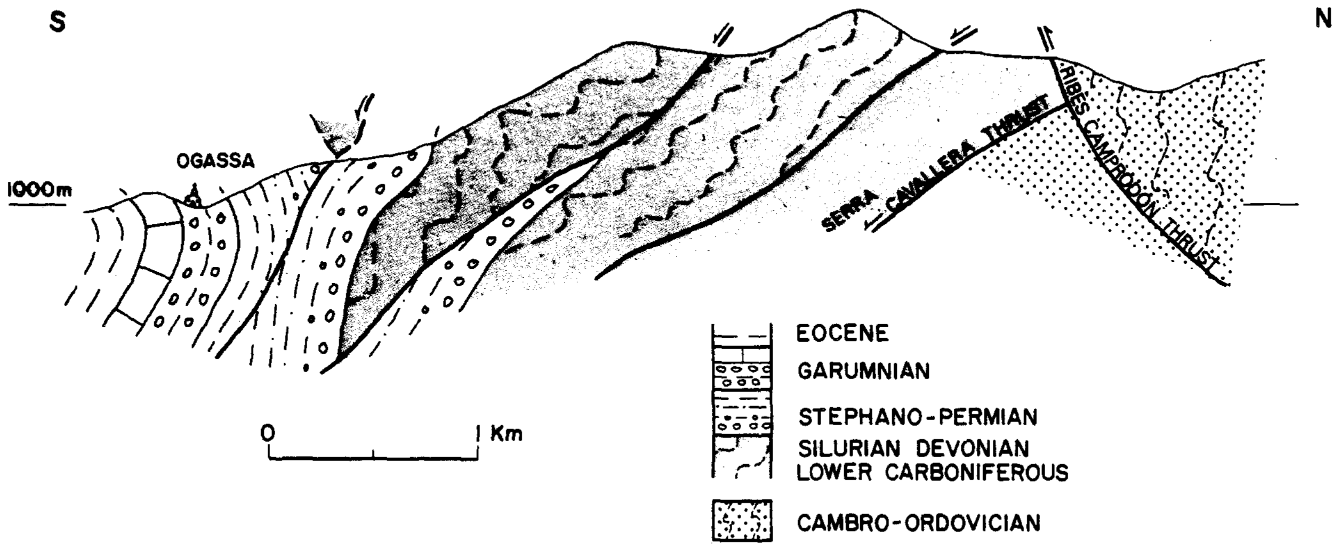

Fig. 5. Cross-section showing the southward-dipping thrusts of the Cadí nappe.

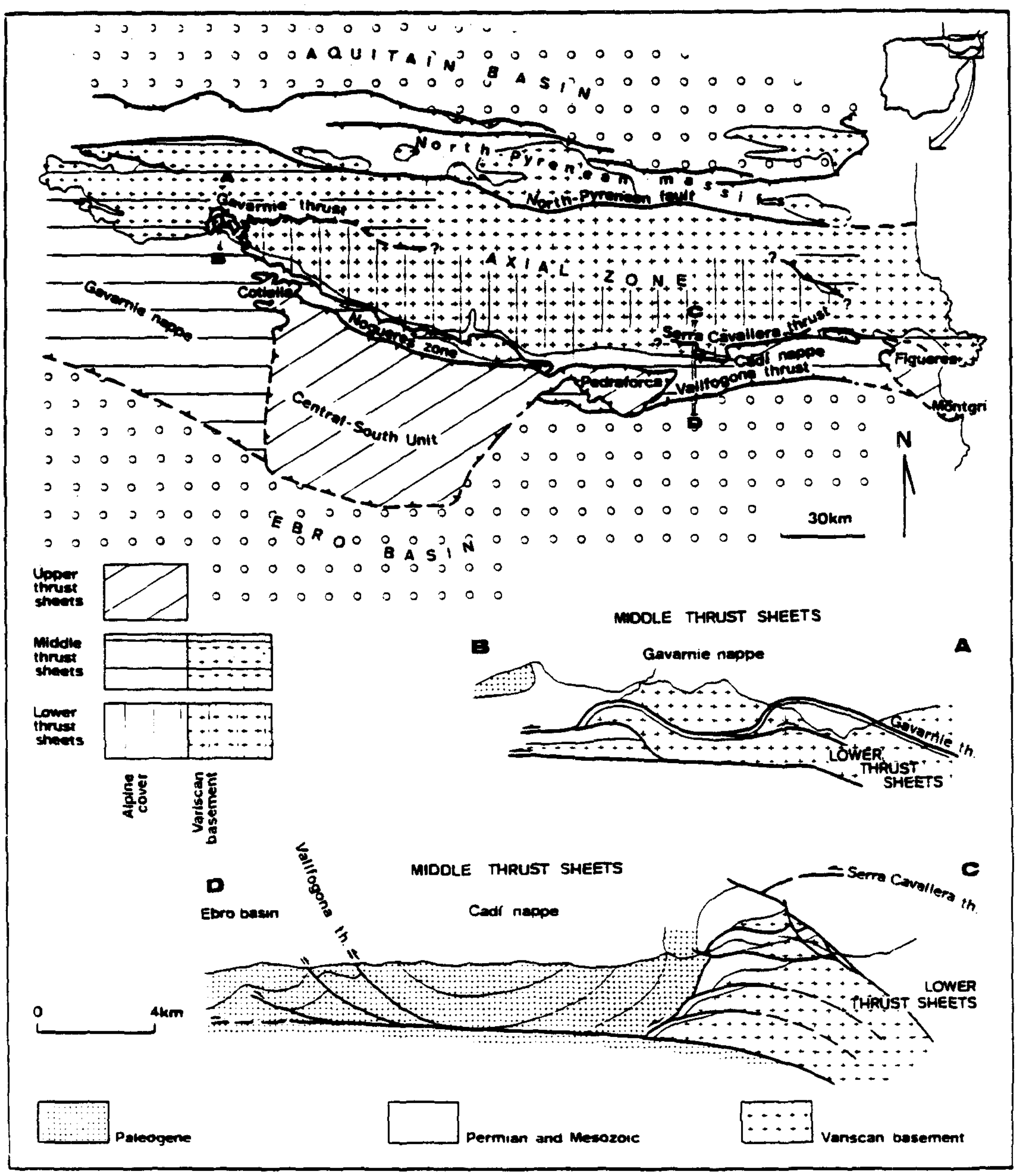

Fig. 6. Sketch-map of the main structural units of the Pyrenees and two simplified cross-sections showing the similarities between the structure at the western and eastern Pyrenees (A–B section, after Parish (1984), simplified).

unit outcrops in two culminations or tectonic windows of kilometric dimensions (Freser Valley and Rocabruna culminations). In the Freser Valley culmination, a minimum 3 km displacement of the Upper Paleozoic basement of the Cadí nappe over the Lower Paleozoic and the cover sequence of the Bruguera thrust sheet can be observed.

With regard to the problem of the continuity of the Cadí nappe towards the west, the following observations allow us to treat the Nogueres Zone as a link between Gavarnie and Cadí nappes; namely, the similarity of the observed downward facing folds, and the similarity in sedimentary characteristics and basement involvement between the two nappes, as discussed above.

From the Freser Valley cross-section (Fig. 4) we can conclude that Alpine thrusts affecting the pre-Hercynian basement produce a piling-up of basement horses. In this way, the Axial Zone does not represent a parautochthonous unit; on the other hand it consists of several basement thrust sheets forming an antiformal stack (Parish 1984, Williams 1985). A remaining problem arises with respect to the position within the Axial Zone of the trailing edge of the southern foreland dipping thrust (Serra Cavallera thrust).

If the former proposed scheme is accepted, a new structural subdivision of the South Pyrenean thrust sheets would be required. There exists a problem with the mapping of Alpine thrusts within the Axial Zone and, hence, with the establishment of structural units. As a first step we propose a new subdivision of the South Pyrenean thrust sheets (Fig. 6), as follows.

(1) *Upper thrust sheets*, consisting of cover thrust sheets with a thick and complete Mesozoic sequence (Cotiella, Montsec, Pedraforca and Figueres–Montgrí thrust sheets).

(2) *Middle thrust sheets*, formed by basement and cover thrust sheets. The basement mainly consists of post-Silurian rocks. The cover is characterized by an incomplete and reduced Mesozoic sequence and by Eocene flysch (Gavarnie–Monte Perdido and Cadí nappes).

(3) *Lower thrust sheets*, formed by a pre-Hercynian basement, consisting of the pre-Silurian rocks outcropping in the Gavarnie tectonic window, Freser Valley and Rocabruna culminations and the main part of the Axial Zone.

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