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STRUCTURE AND ORGANIZATION OF THE PORMA MÉLANGE: PROGRESSIVE DENUDATION OF A SUBMARINE NAPPE TOE BY GRAVITATIONAL COLLAPSE

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ABSTRACT. The Porma Mélange is a unit up to 1 km thick underlying the Forcada Nappe, in the Variscan foreland of the Iberian Peninsula. Most of the Porma Mélange consists of a highly deformed, boudinaged sequence, with extension values over 300 percent. The boudins or mélange blocks are the result of bed-parallel extension in two perpendicular directions giving rise to equidimensional boudins in plan view (chocolate tablet structure). In cross-section view, the boudins show different shapes (rectangular, rhomboid, triangular, trapezoid, or with arrowhead edges) due to various combinations of extension and shear fractures. Both the provenance of the mélange blocks, mostly derived from the upper part of the Bodón Nappe, that overlies the Forcada Nappe, and flattening-type strain ellipsoid shapes support the interpretation that hanging-wall gravitational collapse of these nappes was the cause of the extensional deformation. The current distribution of the mélange blocks from different nappe formations implies progressive unroofing of the nappe stack through subsequent submarine slumps.

The internal structure of the mélange blocks depends on the degree of sediment lithification during slumping and illustrates the significance of the so-called "native" and "exotic" blocks. The source of most of the mélange material (shaly matrix and "native" blocks or boudins) was the semilithified syntectonic sediments of the upper part of the Bodón Nappe, which underwent brittle-ductile deformation (boudinage) during slumping. However, a few and usually larger "exotic" blocks also came into the basin as individual slip blocks from competent well-lithified formations, originally located at the lower part of the nappe stack, with higher shear resistance and less suitable for spreading. Thus, the arrangement of major nappe fragments, traditionally named klippes and showing sizes that may reach up to several kilometers, does not agree with the geometric rules of thrusting, and are reinterpreted as megablocks resulting from gravitational sliding during denudation of advancing nappes.

INTRODUCTION

Frequently, submarine nappes, both in foreland thrust-belts and in accretionary prisms, overlie a rock formation up to kilometric thickness consisting of a mixture of claystones with scattered fragments of harder rocks, extremely diverse in size, belonging to formations of different ages, with no apparent order. These chaotic deposits usually overlie flysch formations and were formerly known as wildflysch but today are called mélanges and olistostromes.

The different names derive from different interpretations regarding their origin. The name "wildflysch" was introduced by Kaufmann (1871). Later, Heim (1908) and Lugeon (1916) were the first to consider that wildflysch deposits were originated by submarine sliding. The term "olistostrome" means slid bed, from the Greek "olistomai" (to slide) and "stroma" (mat or bed). When olistostromes were first defined (Flores, 1955), they were considered as sedimentary deposits.

On the other hand, the term "mélange" was first used by Greenly (1919). He thought mélanges to have been generated by tectonic crushing of a rock sequence that had layers of contrasting competence. Hence, later classification tables, Hsü (1968) and Cowan (1974), make use of genetic definitions according to which mélanges are

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regarded as the result of tectonic fragmentation and olistostromes are interpreted as sediments resulting from gravity sliding. Nevertheless, to avoid controversy on the interpretation of the same block-in-matrix formations, mélanges for some researchers and olistostromes for others, the term mélange in its purely descriptive sense has become widely accepted (Berkland and others, 1972; Hsü, 1974; Raymond, 1975, 1984; Cowan, 1978). Chaotic deposits called mélanges show no true bedding, except for fragments of previously bedded rocks. In recent years, a new term, "tectonosomes" (Pini, 1999), versus olistostromes, has been proposed depending on their structural order. Tectonosomes result from stratal disruption by boudinage and folding, compatible with tectonic deformation and gravitational slumping. The matrix usually displays scaly fabric. Pini (1999) limits the scope of the term olistostromes to chaotic sedimentary bodies characterized by a brecciated matrix and originated by debris flows or debris avalanches.

The key question that commonly arises regarding the significance of the mélanges is whether they were shear zones at the base of subaqueous thrust sheets, incorporating nappe fragments as a result of tectonic brecciation (fig. 1A) (Bailey and McCallien, 1950; Merla, 1951; Vollmer and Bosworth, 1984; Bosworth, 1989; Jeanbourquin and others, 1992), or whether they derive from denudation of moving nappes as gravity landslides detached from the nappe toe (fig. 1B) (Signorini, 1940; Gèze and others, 1952; Abbate and Bortolotti, 1961; Page, 1962; Caron, 1966; Elter and Trevisan, 1973; Hoedemaeker, 1973; Engel and others, 1978; Page and Suppe, 1981; Steen and Andresen, 1997). These chaotic deposits usually contain some few blocks, with very different lithology as compared to the rest of the blocks, known as exotic blocks (Hsü, 1968) in the case of mélanges and exolistoliths (Hoedemaeker, 1973) in olistostromes. Normally, most of the blocks, called "native" in mélanges and "endolistoliths" in olistostromes, are thought to derive from the basin whereas "exotic" blocks would have come from outside the basin. This assumption will be discussed in this paper.

The main objective of this paper is to discuss the origin of the Porma Mélange. Even if the term mélange is associated with chaotic deposits, at the Porma Mélange such chaotic character is only apparent. In the first place shape, attitude and internal structure of the blocks, as well as block-matrix relationships will be described. This will illustrate the process by which the blocks were produced. On the other hand, the blocks are not randomly distributed; statistical distribution of blocks with different lithology and age can be used to infer progressive denudation of the nappe toe.

The aim of this study is to contribute toward a better understanding of submarine nappe denudation by gravitational processes. The information could be useful in interpreting the significance of similar mélanges in other orogens.

REGIONAL GEOLOGY

Geological Setting

The Porma area is located on the southern slope of the Cantabrian Mountains, a block uplifted during Alpine times that exhumes the Palaeozoic basement (Alonso and others, 1996). Geologically, the Porma area belongs to the Cantabrian Zone, the outermost zone of the Iberian Variscan Massif (Lotze, 1945; Julivert and others, 1972) (fig. 2), an A-type subduction orogen (Bally and Snelson, 1980). This zone is characterized by thin-skinned tectonics (Julivert, 1971; Pérez Estaún and others, 1988); low or absent metamorphism and scarce cleavage. Nappe emplacement occurred during late Carboniferous (Middle-Upper Pennsylvanian) times.

The study area extends along the eastern part of two main nappes: Bodón (upper) and Forcada (lower) (De Sitter, 1962; Marcos, 1968a) and their relative autochthon, named Porma Basin (Suárez and others, 1996) (figs. 3 and 4). The Porma Basin contains a mélange cartographic unit and two major allochthonous blocks, known as

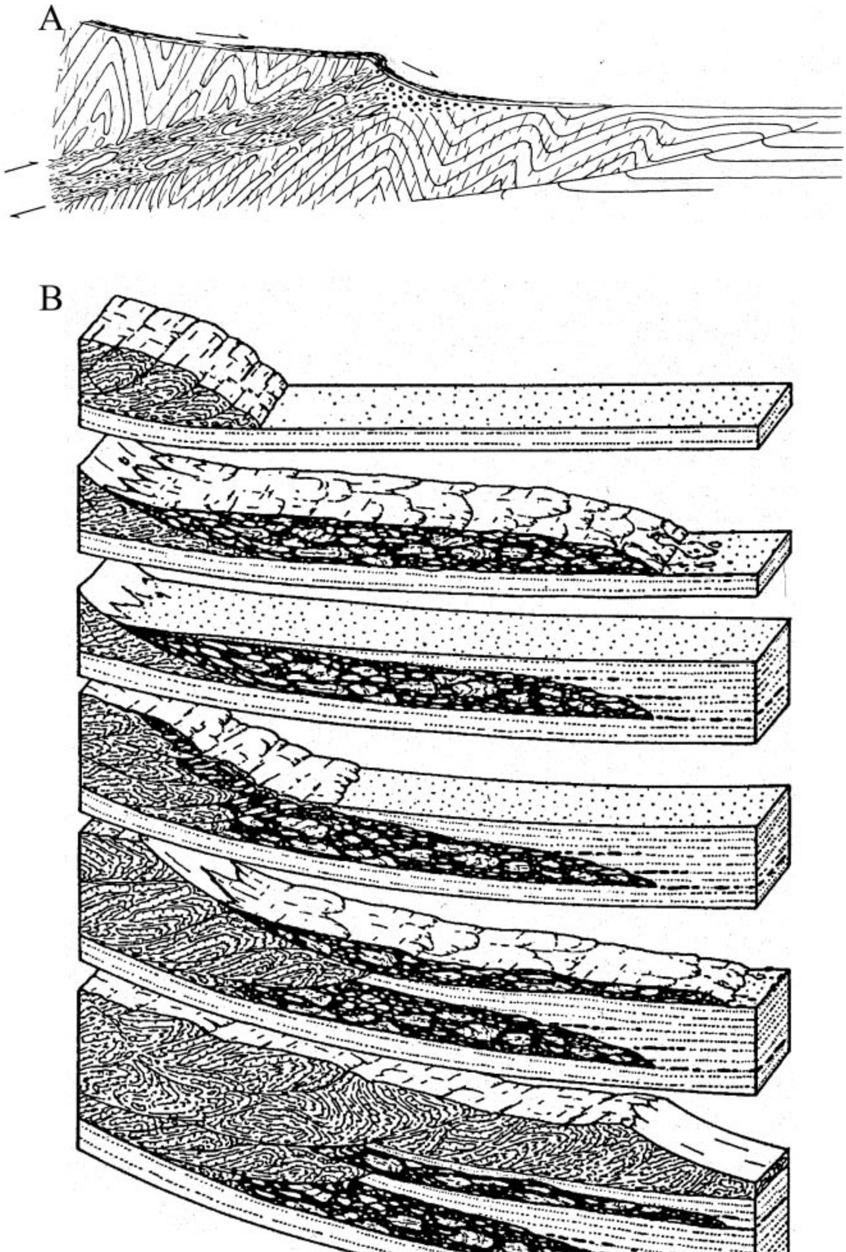

Fig. 1. (A) Model for the origin of a mélange in a foreland overthrust setting (Vollmer and Bosworth, 1984). (B) Emplacement of two olistostromes during the progressive advance of thrust sheets (Elter and Trevisan, 1973).

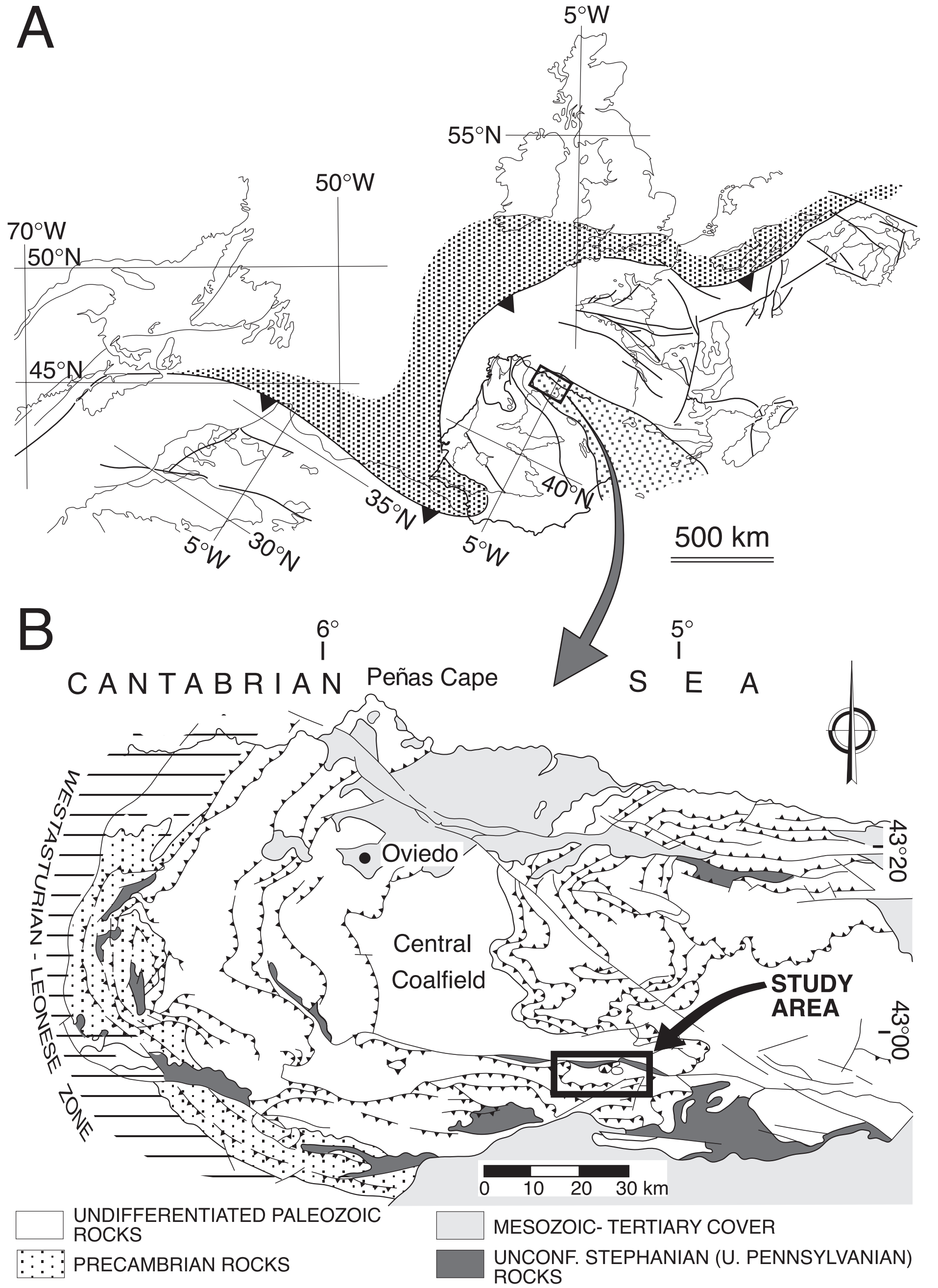

Fig. 2. (A) The Variscan Orogen in Western Europe and North America (reconstruction of the Pangea in the area surrounding Iberia after Lefort, 1989). Closed triangles: Variscan Front; heavy dotted: accretionary prism; light dotted: foreland fold-and-thrust belt (Cantabrian Zone). (B) Location of study area within the Cantabrian Zone.

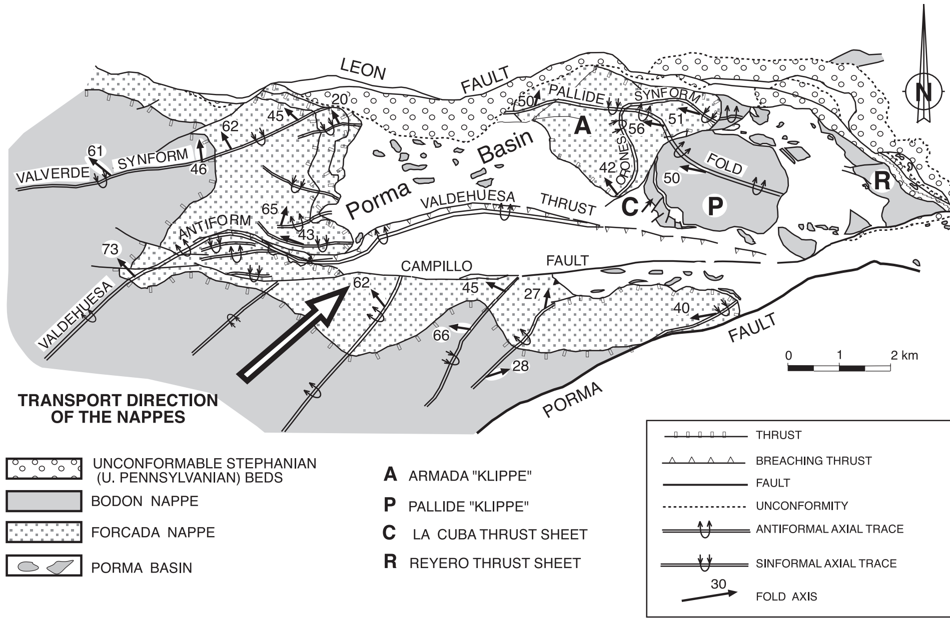

Fig. 3. Structural sketch of the Porma area showing the names of main thrust sheets and folds.

Armada and Pallide “klippes”, which have been related to the two main nappes (De Sitter, 1962; Lobato, 1975) (fig. 4).

In the SE, the Porma Basin is bounded by the Porma Fault (fig. 4) interpreted as a “tear fault” related to the emplacement of the nappes (Alonso, 1987). On the basis of this and of other kinematic criteria, obtained through structural analysis of maps and outcrops, a transport direction from southwest to northeast has been determined for the nappes of the southern branch of the Cantabrian Zone (Arboleya, ms, 1978, 1981; Alonso, 1987; Alonso and others, 1989).

The Porma area is bounded at the N by the León Fault (De Sitter, 1962; Marcos, 1968b), which separates it from the Central Coal Basin (fig. 4). Here, the Carboniferous sequence is different from that in the Porma Basin, because no widespread olistostromic rocks occur. Along this fault there are patches of uppermost Pennsylvanian (Stephanian age) rocks that unconformably overlie thrust surfaces. The deformation of these rocks can be explained as a result of a N-S shortening that led to the tightening and reorientation of previous fold-related thrusts and to the overturning of thrusts in the southern part of the Cantabrian Zone (Alonso, 1989).

Stratigraphy of the Bodón and Forcada Nappes

The lithostratigraphic features of these nappes are well known after the studies by Comte (1959). A Lower Cambrian to Carboniferous stratigraphic succession forms them and displays a large stratigraphic gap due to erosional processes related to unconformable Upper Devonian rocks. The stratigraphic gap is wider at the Forcada than at the Bodón Nappe (fig. 5). The stratigraphic succession of these two nappes shows further differences, namely: i) the occurrence of Lower Cambrian Herrería Formation in the Bodón Nappe; ii) the occurrence of massive Carboniferous limestones (Valdeteja Formation) at the Bodón Nappe (except for the easternmost end) and the Ricacabiello Formation (Sjerp, 1967) in the Forcada Nappe (fig. 5).

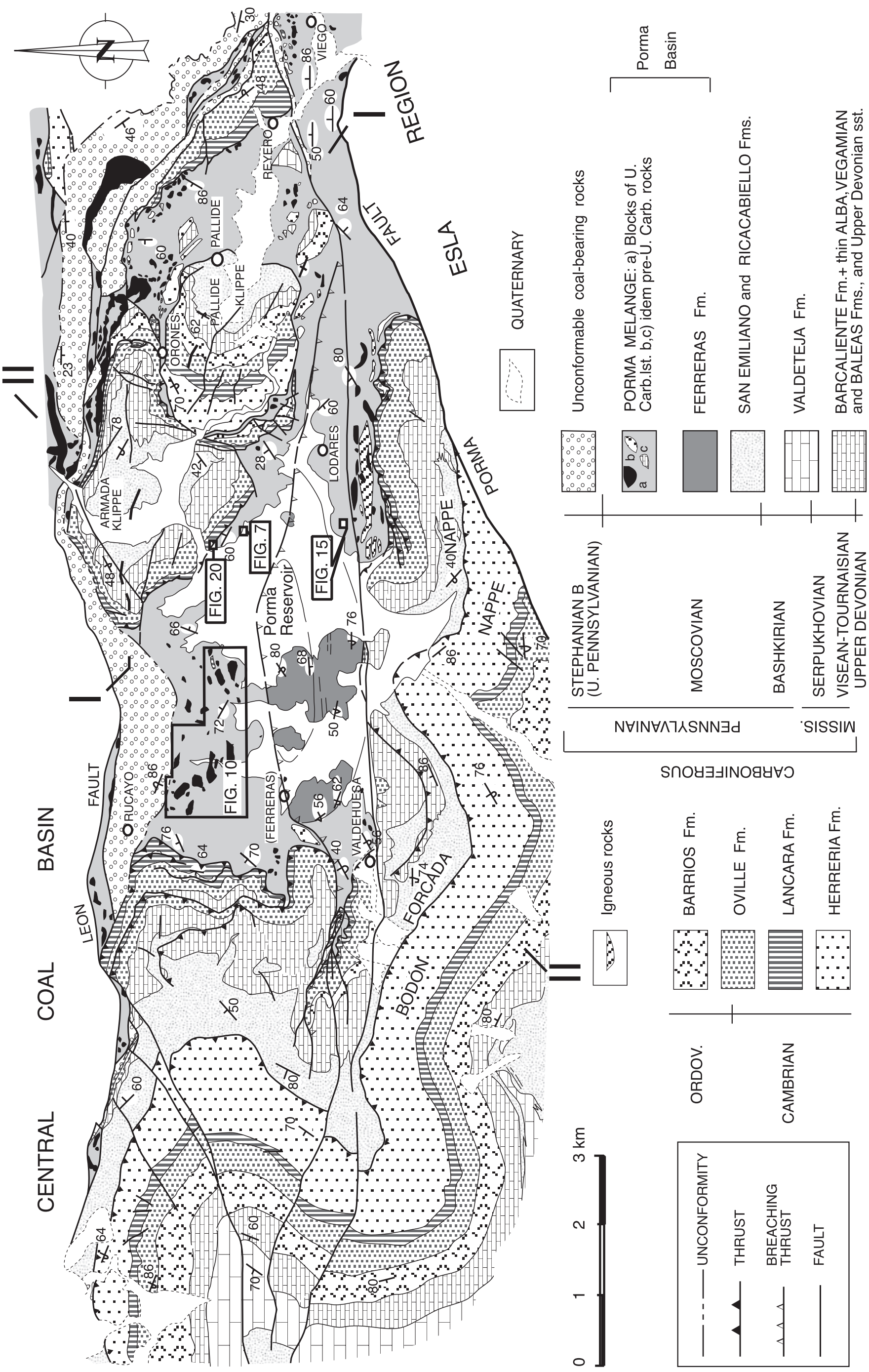

Fig. 4. Geological map of the Porma area. I-I′ and II-II′: location of geological cross-sections of figure 6.

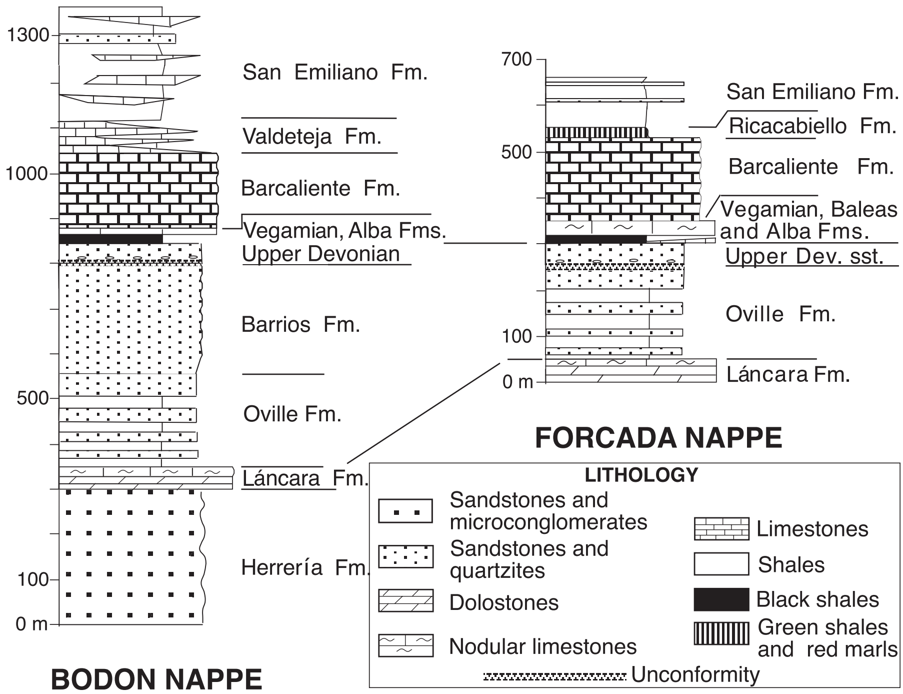

Fig. 5. Stratigraphic columns of the Bodón and Forcada nappes after Comte (1959), Sjerp (1967), Wagner (1963) and Wagner and others (1971).

With regard to the stratigraphy of the “klippen”, the succession recorded at Armada can be correlated to that of the frontmost sector of the Forcada Nappe (Lobato, 1975) whereas that of Pallide is similar to that of the eastern sector of the Bodón Nappe.

Stratigraphy of the Porma Basin

Some stratigraphic features of this sequence, located at the footwall of the Forcada Nappe, were outlined by Evers (1967). This author describes a ca. 1000 m thick succession (Ferreras area flysch) constituted by graywackes, sandy shales and limestone lenses.

The succession has been divided into two cartographic units (Suárez and others, 1996) whose distribution can be seen in figure 4. The lower unit (Ferreras Formation) is a well-stratified graywacke and shale sequence often with turbiditic features.

The upper unit (the Porma mélange) is up to 1,5 km thick (fig. 6B). It is an essentially lutitic formation including an apparently chaotic mixture of blocks with varying lithology and provenance. Alberts (ms, 1985), Tromp (ms, 1985), Nijman and Savage (1989), and Suárez and others (1996) have interpreted this unit as an olistostrome. The most common blocks are limestone and graywacke fragments derived from the synorogenic Carboniferous sequence. The limestone blocks may reach outcrop widths of up to kilometric size and consist of light gray limestones, sometimes with algae lamination, fusulines, ooids, which imply platform provenance. These blocks have been dated between the Upper Baskhirian and the Lower Podolskian (Rupke, 1965; Evers, 1967; Navarro and others, 1987; Heredia, ms, 1991; Elisa Villa, Department of Geology, Oviedo University, personal communication). Graywacke

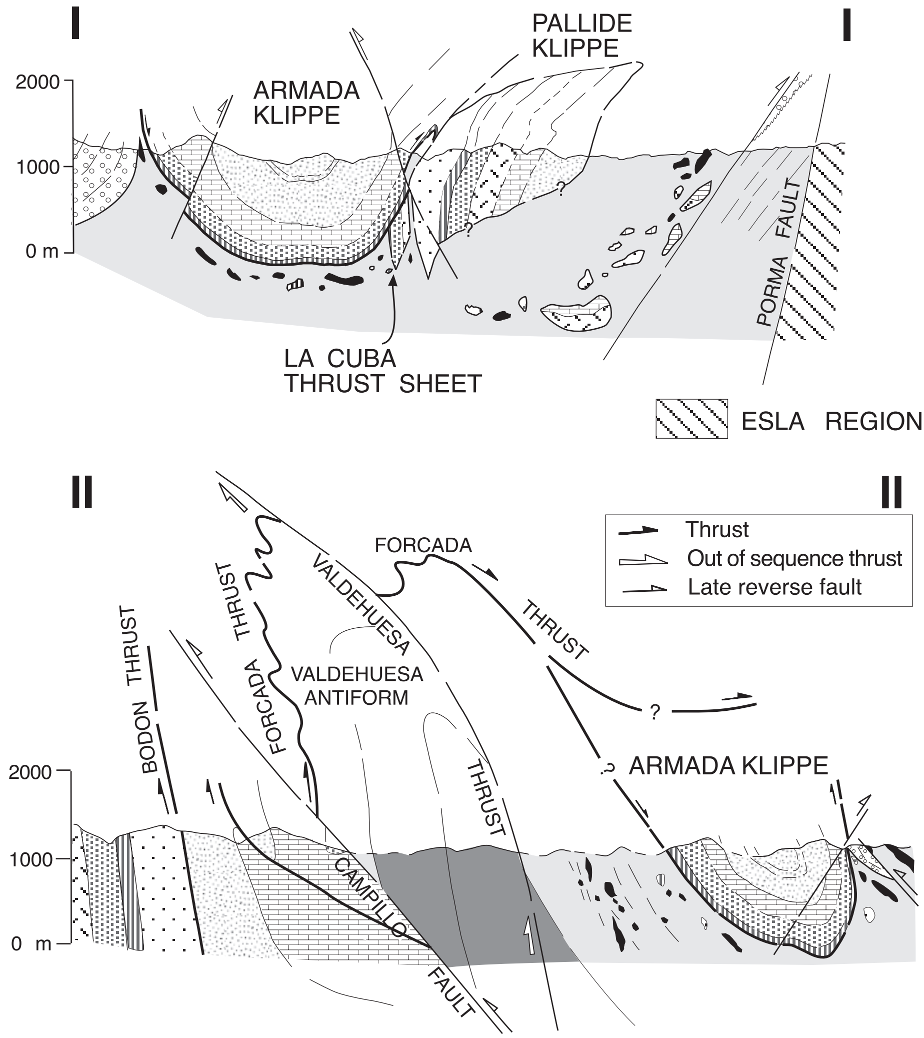

Fig. 6. (I-I) Geological section through the Armada and Pallide klippes (Suarez and others, 1996). (II-II′) Geological cross-section along the transport direction of the nappes. Location and stratigraphic legend in figure 4.

blocks are usually of metric scale or smaller, and thereby have not been represented in figure 4. Frequently, these fragments of wacke beds display groove and flute casts.

There are also blocks derived from the preorogenic pre-Carboniferous sequence, some of which (quartzites from the Ordovician Barrios Formation, sandstones from the Cambrian Herrería Formation) occur just in the Bodón Nappe (fig. 4).

Structure of the Bodón and Forcada Nappes

The structure of these nappes in the study area is quite simple and can be well explained as a result of ramp-flat geometry of thrust surfaces. Both thrust sheets exhibit hangingwall flats underlying the Herrería Formation in Bodón and the Láncara Formation in the Forcada Nappe (figs. 3 and 4).

As for the footwall, whereas the Bodón thrust displays a flat over the San Emiliano Formation, the geometric relationship of the Forcada thrust sheet with its autochthon is less clear. There is also a footwall flat of the Forcada thrust sheet over its autochthon although the relation is complicated by: i) the Campillo Fault (figs. 3 and 6B), that produces a stratigraphic omission of up to 400 meters at the Forcada Nappe and at the Porma Mélange, east of Valdehuesa; and ii) the Valdehuesa breaching thrust that cuts across the Forcada Thrust (figs. 3, 4 and 6B) (Suárez and others, 1996).

These thrusts display winding traces because they are jointly deformed by several reclined folds, the axial traces and axes of which are shown in figure 3.

Structure of the Porma Basin and Thrust-Fold Relationships

The stratigraphic sequence of the Porma Basin has been strongly folded together with the Bodón and Forcada nappes. The outcrop pattern of the Porma area shows duplication of the Porma Mélange with the Ferreras Formation in the middle (fig. 4). The persistent southward younging of the turbidite beds allows the duplication of the mélange to be explained as a result of an east-west trending thrust (Valdehuesa Thrust, figs. 3 and 6B). Such thrust cuts across the Forcada Thrust and folds it at the Valdehuesa Antiform. Ahead of the Valdehuesa Antiform, the Valverde-Armada Synform occurs. Both folds display parallel axial traces and can be explained as a fold-pair accommodating Valdehuesa Thrust displacement as in the models of fault-propagation folds. To the west, both folds trend northeast southwest, which may be interpreted as a lateral structure of the Valdehuesa Thrust, taking into account the northeast transport direction of the nappes.

The Bodón, Forcada and Valdehuesa thrust sheets are deformed by other north-south folds, south of Campillo Fault (fig. 3), which can also be related to lateral structures.

THE PORMA MÉLANGE: DESCRIPTION

Composition. Deposit Terminology

The Porma Mélange is composed of two different types of rock bodies. Most of the Porma Mélange consists of a boudinaged sequence of Pennsylvanian age, with very high extension values. This sequence includes scattered "exotic" blocks, up to kilometric size, with a range of ages from Lower Cambrian to Lower Carboniferous. The Porma Mélange is regarded as the result of stacking of submarine landslides (boudinaged sequence) intercalated with individual slid blocks (exotic). The boudinaged sequence derived from the semilithified Pennsylvanian synorogenic sequence, a shallow marine succession located at the upper part of the highest nappe. This sequence could also be called "broken formation" s*ensu* Raymond (1984) or "tectonosome" *sensu* Pini (1999). The exotic blocks derived from the well-lithified pre-Uppercarboniferous formations, originally located at the lower part of the nappe stack.

According to Coussot and Meunier (1996), landslides essentially originate in internal fractures whereas some parts can undergo continuous deformation. As a result, the initial structure of the material may be partially observed in the final deposit. In contrast to landslides, olistostromes in the sense of Pini (1999) are the result of debris flows, during which the initial structure of the material is completely distorted. In the Porma Mélange, the initial structure of slid material, although highly destructured, can be recognized as a boudinaged sequence. Consequently, the term "block", commonly applied to mélanges, rather than "olistholith", used to refer to olistostromal bodies, will be used here and the term mélange will have no genetic significance (AGI Glossary of Geology), but will refer just to the mixture of fragments and blocks of all sizes, both exotic and native, embedded in a matrix of finer-grained material (Raymond, 1984).

Block Shapes. Block-Matrix Relationships

At first sight the Porma Mélange looks like a chaotic deposit with blocks of different sizes and lithologies, all mixed together with no apparent order (fig. 4) and included in a shaly matrix. However, a closer look at the outcrops shows that the geometrical relation between blocks and matrix results from a boudinage process with very high extension values. Figure 7A shows boudinaged graywacke beds. Here, blocks and matrix are well exposed, which makes it possible to see that the blocks are clearly boudins, surrounded by cleaved shales.

The role played by mesoscale shear fractures in the development of boudins of the Porma Mélange is also particularly well exposed here. Blocks are commonly bounded and transversed by shear fractures causing layer-parallel stretching. The shape of the blocks varies in cross-section, depending on whether the ends of the boudin are two parallel fractures (rectangular- or rhomboidal-shaped boudins a, c, e, g, h, l, k, n and o in fig. 7), two conjugate faults (trapezoidal-shaped boudins b and m in fig. 7), or whether one of the ends resulted from a combination of two conjugated faults (spearhead end boudins f, y, j in fig. 7). There is also a barrel-shaped boudin (e) that results from extension fractures (fig. 8A).

Three-dimensional geometry of fractures is well illustrated on bedding surfaces (figs. 8B and 9A), where two sets of fractures are usually observed whose cutoff lines with bedding are subperpendicular. Nevertheless, more complicated fracture patterns in plan view can also be found (fig. 9B). The intersection of these sets of fractures and the bedding controls the three-dimensional shape of the boudins, which tend to be equidimensional (commonly rhombohedral and also polyhedral, whenever there are spearhead or rectangular ends).

The orientation of fractures, striations and bedding is shown in figure 7B. It indicates layer-parallel extension in two different directions, which is consistent with a weak cleavage in the matrix that parallels bedding, evidencing a layer-perpendicular shortening direction. The cleavage is deflected around boudins, with a tendency to follow the block surface. Nevertheless, when the block face is a fault at right angle to the cleavage, as it is the case with some boudins ends, the cleavage is interrupted by the block surface (fig. 7A). This cleavage resembles what some authors have called scaly fabric (Pini, 1999; Vannucchi and others, 2003) or phacoidal cleavage (Vollmer and Bosworth, 1984; Bosworth, 1989) in other block-in-matrix formations. At centimetric-millimetric scales, the lens-shaped scales result from anastomosing, striated, polished surfaces. The sedimentary phyllosilicates display a strong parallel preferred orientation under the optical microscope.

West of the Porma reservoir, outcrops commonly contain boudinaged limestone and graywacke beds. The mélange here contains limestone blocks up to tens of meters thick and hundreds of meters long. Their shape and arrangement are shown in figures 10 and 11. Usually the blocks are well exposed but the structure of the matrix cannot generally be studied due to its very scanty and poor exposures, except along reservoir border, where the waves beat the shores (fig. 7 shows one such area at a time when the water level is low). On the other hand, even in those cases in which the structure of the matrix cannot be studied, the shape and internal structure of the blocks provide relevant information. Figure 11 shows a close view to a selected area, illustrating the geometry and arrangement of the minor limestone blocks, which cannot be represented with the scale used in figure 10. These limestone blocks are similar in shape and arrangement to those wacke blocks described above. The individual blocks are bounded by faults displaying striations (fig. 12). The range of block section shapes includes: rhomboid, triangular and trapezoid shapes, some of them with spearhead

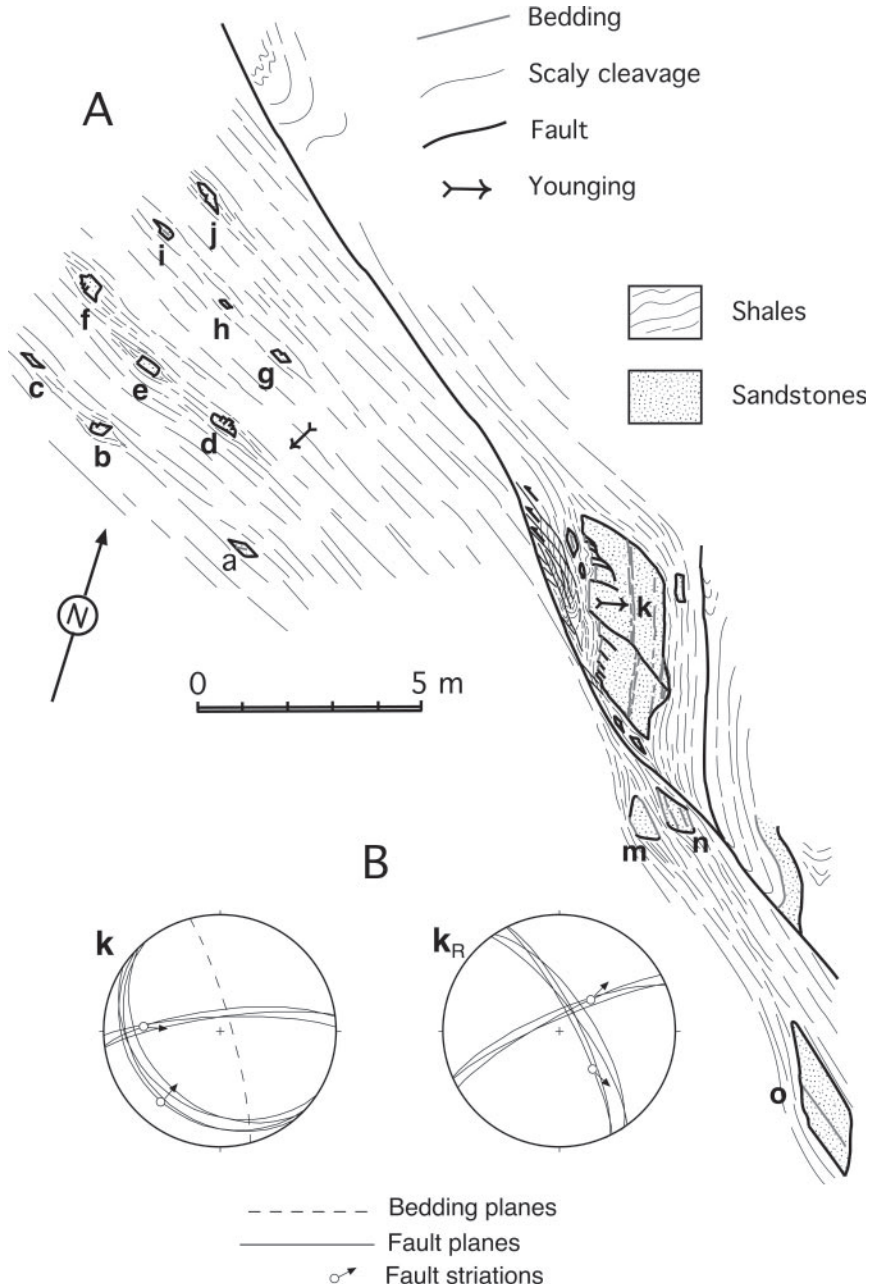

Fig. 7. (A) Boudinaged graywacke beds included in shaly matrix. Note that the cleavage in the enclosing shale is parallel to the trains of bed fragments. Location in figure 4. (B) Stereoplots of structural elements of the k boudin in figure 7A. Stereoplot k: current attitude of the extensional faults and bedding; Stereoplot k_R: after restoration of the bedding to a horizontal attitude.

ends (block a in fig. 11A). Only the smaller ones, up to ca. 1 meter thick, located between blocks e and f are rectangular, which is in accordance with theoretical and experimental work by Mandal and others (2000).

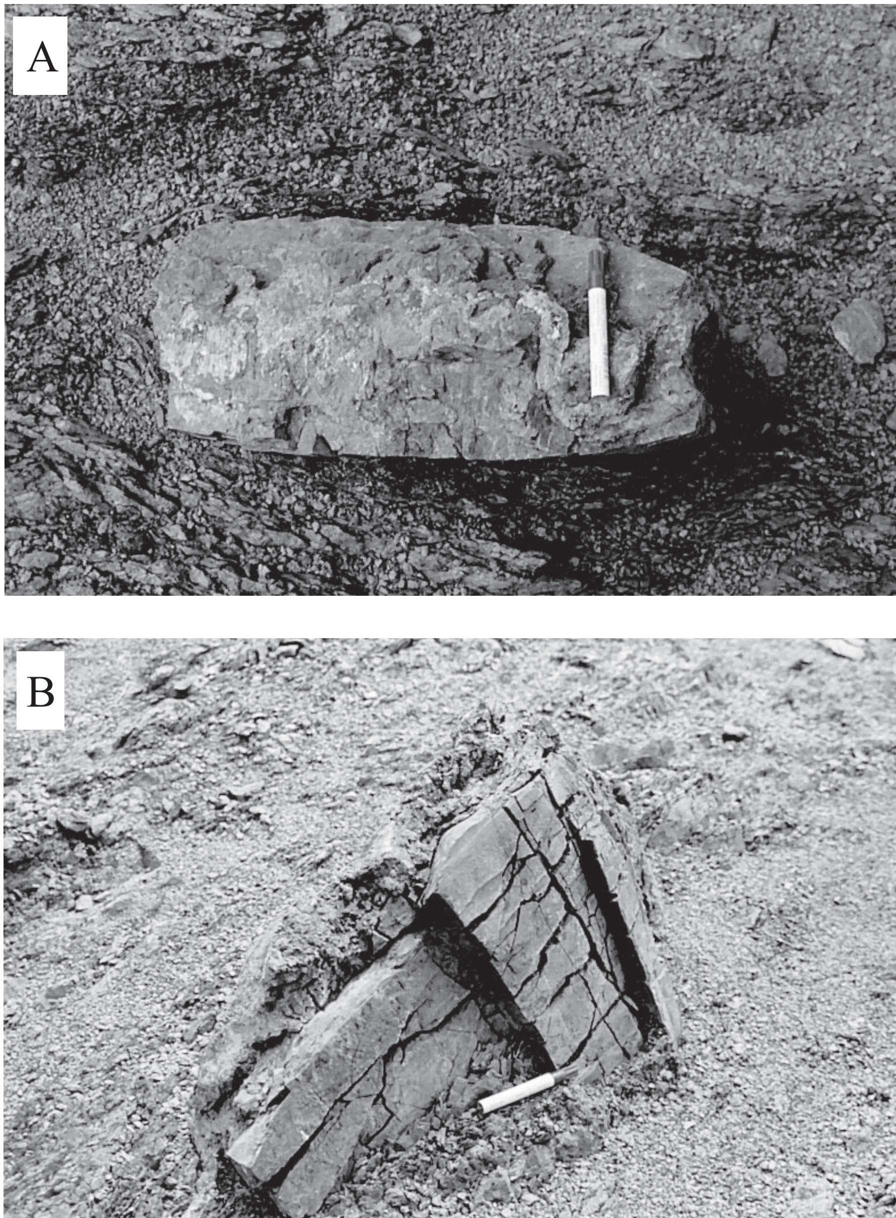

Fig. 8. Photographs of the e and d boudins in figure 7A. (A) Cross-sectional view of boudin e. (B) View of the bedding surface in the d boudin showing two sets of extensional fractures.

Figure 11B shows little variability in block orientation (direction and dip of bedding and shear surfaces) in spite of being relatively far apart (fig. 11A). Beds generally dip to the north within blocks. Faults commonly dip steeply (figs. 11B and 12). At some outcrops the listric shape of some of the faults can be seen (cross-section I-I′ in block d, fig. 11B), as well as some conjugate faults in boudin boundaries (cross-section II-II′ in block c, fig. 11B). In the southern part of these cross-sections, the

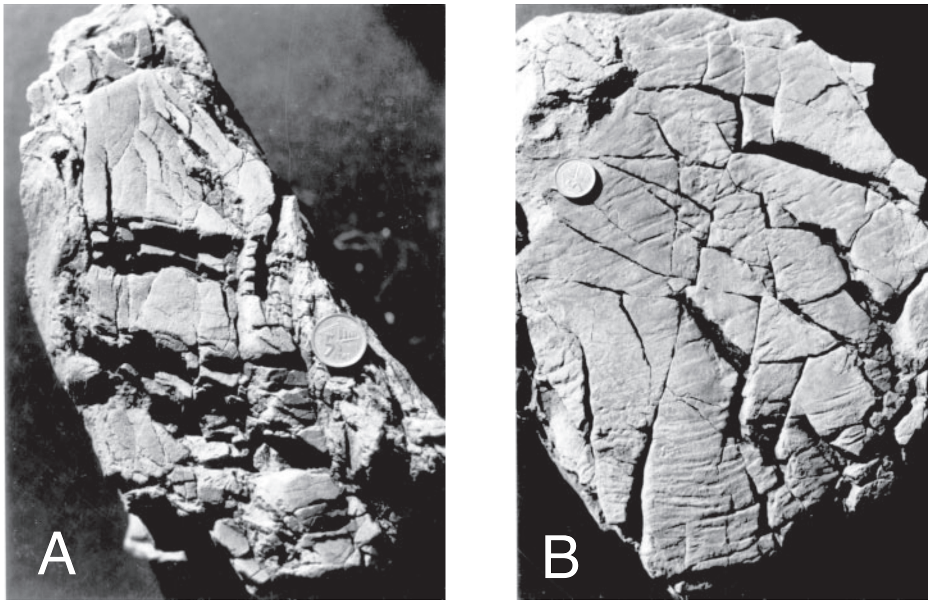

Fig. 9. Fracture patterns at the bottom of two graywacke blocks. (A) Two sets of subperpendicular extensional fractures. (B) Several sets of extensional fractures, two of which are subperpendicular.

relation with the shaly matrix, with cleavage running parallel to the faults that limit the blocks, can also be observed.

The arrangement of the blocks of figure 11 suggests that they are part of bedded units that have been stretched and separated as a result of boudinage. In fact, most of them display the same orientation and those sharing the same lithology are lined up in an echelon arrangement. The staircase arrangement of rectangular boudins results

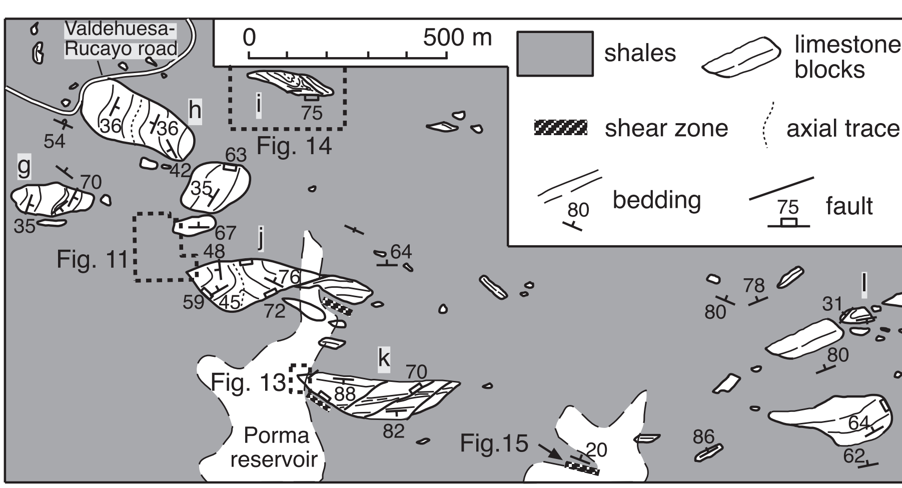

Fig. 10. Geological map showing mélange blocks in the western part of the Porma Basin. Location in figure 4.

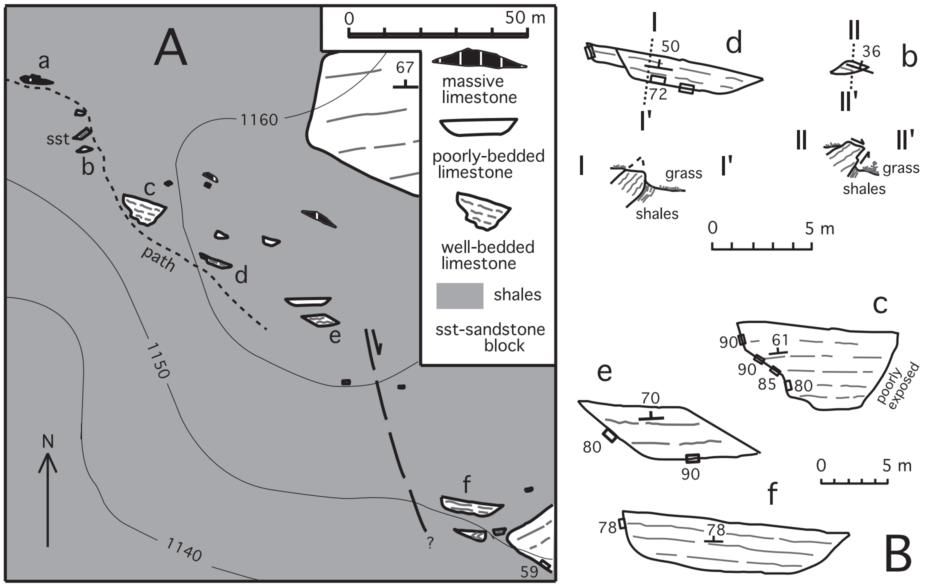

Fig. 11. (A) Arrangement of some minor blocks of figure 10. (B) Detailed sketch showing the shape and true orientation of the blocks. I-I′ and II-II′: sections across blocks d and b.

from stretching of beds oblique to principal strain axes (Ramsay, 1967, figs. 3-50) but in rhomboid boudins, the echelon arrangement occurs even if they derive from beds oriented parallel to the major axis of strain ellipse in coaxial deformation (Mandal and Khan, 1991). If so, the long axes of lozenges become parallel to cleavage (Tyler, 1975). The fact that adjacent boudins (fig. 11) would not fit well if they were relocated together, may be attributed to extensions in two different directions, as can be seen in the fractures of the smaller wacke blocks intercalated in the limestone blocks (figs. 8B and 9).

The geometry of some of the hectometric megablocks does not differ from that of the minor blocks; they are also angular in shape and are bounded by faults or shear zones (fig. 10). The western end of the biggest limestone block (k in fig. 10) is well exposed on the reservoir shore and illustrates well the features of the block boundaries (fig. 13). It is a spearhead end. The northern boundary of the block is a narrow shear zone where phacoidal cleavage developed; C′-type shear bands indicate a sinistral sense of shear. The southern boundary is a fault. Beneath it another shear zone, two meters thick, occurs. This will be dealt with later in the section devoted to shear zones. Inside the limestone block there is a northwest-dipping shear zone, up to one meter-wide, with internal cleavage and anastomosing C- and C′-type shear bands (Berthe and others, 1979); within the shear zone some limestone lenses remain undeformed.

Figure 13C shows projections of the different structural elements of figures 13A and B. The sense of relative motion has been determined from C′-type shear bands and striations. These extensional faults and shear zones, now reverse, become normal faults whenever the bedding is restored to the horizontal attitude.

The shear zone within the limestone block does not seem to shift the boudin boundary, even though its displacement seems to be large taking into account the lack of correlation between the limestone beds on each wall (fig. 13). This type of relation is also observed in some of the faults cutting across the boudins causing either no

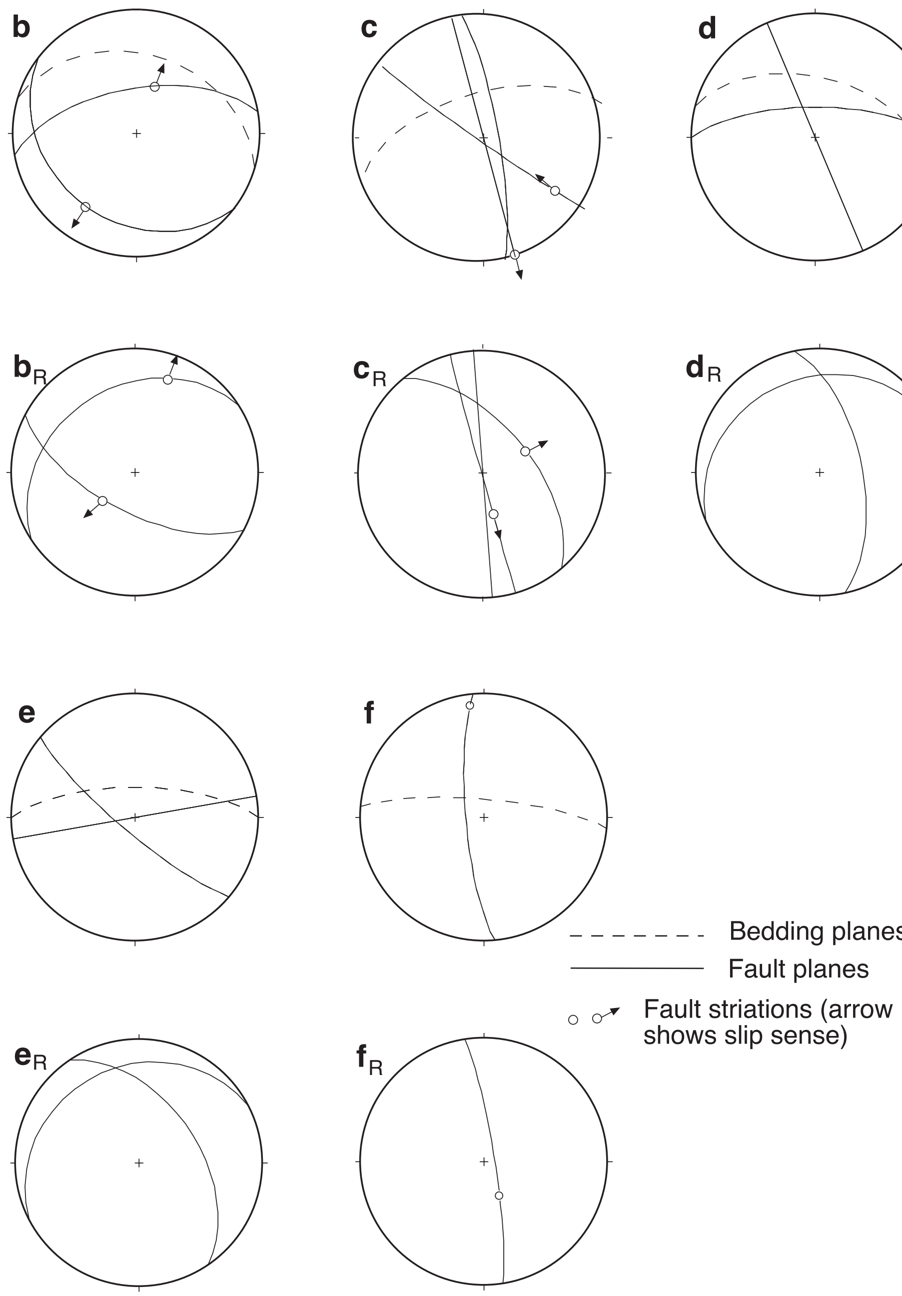

Fig. 12. Stereoplots of structural elements of some blocks in figure 11. Plots with subscript (R) in their labels show the attitude of the fault planes and striations after restoration of the bedding.

displacement of the boudin boundaries at all or, if so, shifting only one of them, although the displacement inside the blocks is remarkable (see fig. 7; boudins j and k in fig. 10; boudin d in fig. 11B). This implies that the faults occurred before the boudin development and not after it. However, its extensional nature and its similarity with the

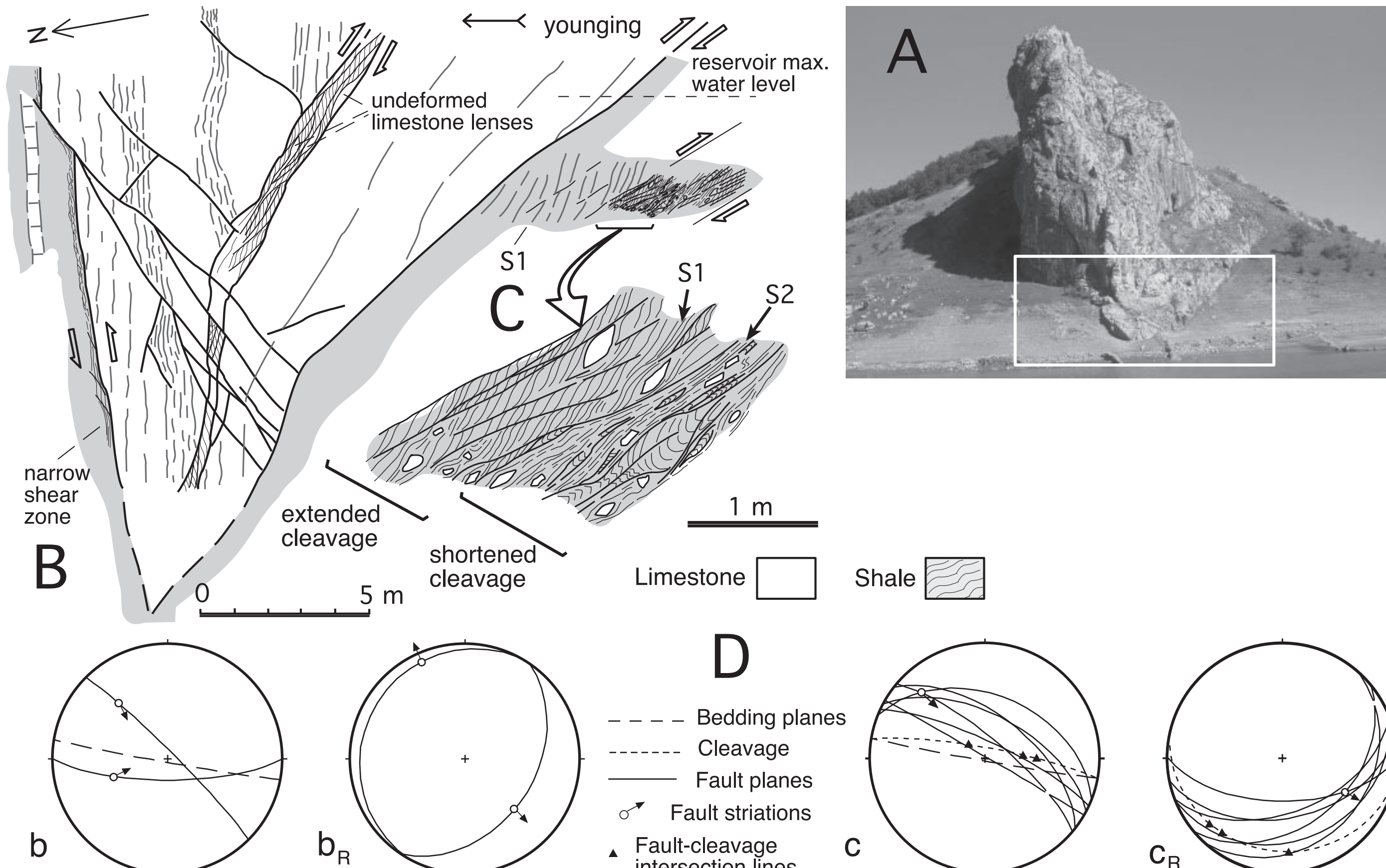

Fig. 13. (A) Photograph of a spearhead end of a limestone megablock. Location in figure 4. (B) Detailed field map of the white square area in A. (C) Enlargement of the shear zone underlying the megablock. (D) Stereoplots of structural elements of figures 13 B and C. Plots with subscript (R) in their labels show the attitude of the structural elements after restoration of the bedding.

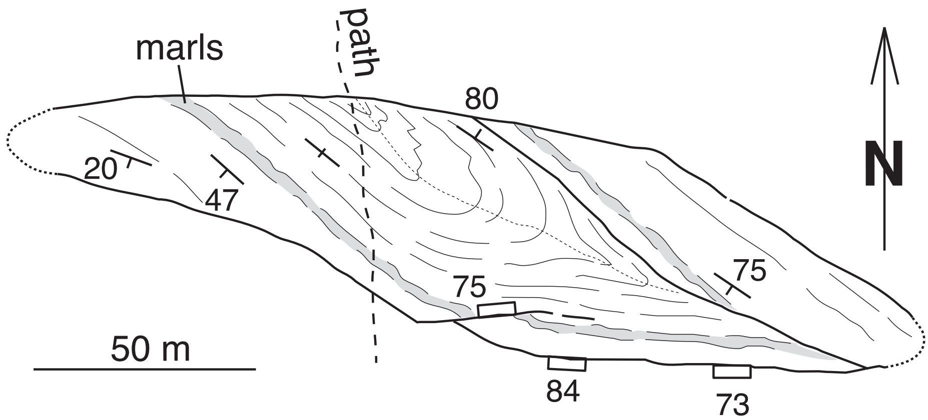

Fig. 14. Limestone block preserving a previous fold. Location in figure 10.

faults limiting the boudin boundaries, allows them to be associated to the boudinage process, even if they do not match boudin boundaries, or do so only partially. This is because the boudin boundaries have used later faults (northern boundary of j block in fig. 10) or two different bedding surfaces connected by faults (northern boundary of k block in fig. 10). We consider all, earlier and later, normal faults causing boudinage to be a result of the same extensional process. In normal fault systems, fault propagation and activity have a complex history (Ackermann and others, 2001): for instance, the number of faults and fault length increases with increasing extension, but the proportion of active faults decreases.

The boudins or blocks so far described (most of the Porma Basin blocks) resulted from the extension of a succession of flat beds. Nevertheless, there are some large blocks (g, h, i, j, l blocks in fig. 10), essentially located west of block k, which present previous folding. A close-up view of one of the blocks is seen in figure 14; bedding within the block is tightly folded and this folding pre-dates emplacement or isolation of the block. The shape of these previously deformed blocks is more irregular than in those described above and, although the dip directions of the strata are also more variable, the fold axial traces always trend between NW-SE and N-S. The meaning of these blocks with early folding will be discussed later.

Bulk Deformation. Strain Values.

Except for some particular zones with simple shear, the type of total strain at the scale of hand specimen and outcrops recorded by small-scale structures of the Porma Mélange (extension and shear fractures in stiff layers and cleavage in mudstones) corresponds to a flattened elongate ellipsoid with the XY plane parallel to the bedding plane (figs. 7, 8 and 9). In other words, tension fractures are orientated approximately normal to layering, cleavage is parallel to bedding, and shear fractures are usually inclined >45° from the top surface of beds and are extensional faults. Maximum and minimum principal stresses were oriented respectively normal and parallel to layering at the instant fractures formed. There are two different fracturing systems in bedding plan view, each of them including two conjugate shear sets and a set of cracks, resulting in layer-parallel extension in two perpendicular directions (figs. 7B, 8, 11 12 and 13). This rules out simple shear (two-dimensional) strain because this implies plane strain conditions. Although, as Cowan (1982) claimed, considering just the shape of the total strain, it is not possible to establish whether a strain path was coaxial or non-coaxial

(Hobbs and others, 1976), the preponderance of structures recording layer-parallel extension together with the almost complete absence of folds suggest that layering was oriented at low angles, or parallel to the XY planes of both infinitesimal and finite strain ellipsoids. Another fact that supports this interpretation is the almost complete parallelism between the bedding of equant and elongate blocks (fig. 11), which implies that rotation was not very significant in neither of the block types (Ghosh and Ramberg, 1976), that is, a coaxial strain path with plane XY nearly parallel to the bedding occurred. The slight rhomboid block rotations observed may have resulted from pure shear with normal to bedding shortening (Mandal and Khan, 1991; Passchier and Druguet, 2002).

Strain determinations in the Porma Mélange are difficult to obtain because strains are commonly very large. Estimation of strain is based on degree of bedding disruption, but commonly beds become difficult to trace as boudins experience great separation. However, whenever boudin trains from the same bed can be noticed, the size of the boudins is remarkably regular and so is the length of the gaps between them (figs. 7A and 11). The fact that the blocks lack a good structural fitting when opposite adjacent boudin faces are put together can be explained as a result of extension occurring in two different directions.

On the other hand, estimating the strain in layers disrupted by boudinage implies certain difficulties, already discussed by Ferguson (1981), deriving from the sequential development of the boudins during extensional processes. In the Porma Mélange, the map section is close to one of the extension directions (fig. 7), and thus the value of the extension parallel to regional strike (northwest-southeast) has been estimated directly on the map, following Ferguson's considerations (1981, fig. 1). In this way, extension values similar for small (fig. 7A), medium (fig. 11) and large blocks are obtained (fig. 10), of about 300 percent. These must be considered minimum values to which the extension recorded by the internal fracturing of the boudins, rarely exceeding 20 percent, must be added.

The subperpendicular extension that is, the dip-parallel extension, is more difficult to determine, given the lack of adequate outcrop sections. However, by observing the hand specimens, it appears similar to that of the strike-parallel extension, producing a bulk strain state with $\lambda_1 = \lambda_2 >> 1 >> \lambda_3$, and λ_3 normal to bedding.

Internal Structure of Blocks. Relationships Between Composition, Internal Structure and Size of Mélange Blocks: Degree of Lithification During Deformation.

The extent of fracturing in the blocks varies and, in some cases, they have undergone plastic deformation. The wacke blocks commonly display pervasive cracked bedding surfaces, due to closely spaced extension fractures, orientated approximately normal to layering, and extensional shear fractures, which sometimes also open (figs. 8 and 9). Some cracks were intruded by adjacent mudstone matrix. Most of the microfaults are confined to a band at the bottom of the turbiditic layers and rarely extend through the entire layer (fig. 7). In many boudins the fractures are confined to the less lutitic zone of the beds, normally the litharenitic base. The fracture's displacement decreases towards the inner part of the beds where it vanishes, probably due to ductile deformation. Sometimes, however, curved normal faults concave downwards, roof in a detachment within the bed (fig. 7A, northern end of boudin k). Upwards, the deformation must be ductile since the displacement of the roof fault disappears (boudin k in fig. 7A).

Unlike wacke boudins, limestone boudins show little or no internal deformation. In the limestone blocks, the faults, if there are any, are widely spaced and cut across the whole boudin without noticeable displacement changes (blocks j and k in fig. 10, block d in fig. 11). This indicates a more brittle behavior than with wacke boudins, lacking ductile deformation.

The difference regarding the internal deformation and ductility between graywacke and limestone blocks, both of them derived from upper Carboniferous (Pennsylvanian) synorogenic sequence, in a non-metamorphic area like the one under study, can be attributed to different degrees of lithification depending on the different rock composition. It is a well-known fact that limestone lithification occurs faster than sandstone lithification (Tucker, 1991). This suggests that deformation occurred when the wackes were still imperfectly lithified. Microfractures developed in the graywacke boudins of the Porma Mélange resemble soft-sediment microfractures named hydroplastic fractures by Petit and Laville (1987).

The shaly matrix must have a more ductile behavior, which is recorded both by the development of boudinage and by scaly cleavage development in the matrix.

The maximum size of the blocks also seems to depend on the degree of lithification of the rocks, since it depends on their age and composition. With regard to the blocks derived from synorogenic sequence, the wacke blocks are usually much smaller than carbonate rocks, often composed of limestone and marl bedded units. Hence, wacke blocks are decametric just in some exceptional cases, and therefore it has not been possible to represent them on the map in figure 10, while hectometric size is common in carbonate blocks (fig. 10). The bigger decametric wacke blocks are in fact multilayer boudins (Ghosh and Sengupta, 1999) composed of alternate thick wacke and thin shale beds. Figure 15 shows the internal structure of one of these blocks. Bedding has a subvertical south-younging attitude. A major fault F, displays flat on ramp in the lower part of the outcrop and flat on flat in the upper part. The main feature of the fault surface is a corrugated, rough morphology, due to numerous later minor extensional fractures whose details are shown in figure 15B. Another fault system consists of south dipping faults, some of which cut across the main fault F (figs. 15A and B). If the footwall bedding of fault F is restored to a horizontal position, these faults become normal faults. Cutoff lines of fault F and of minor extensional fractures are subparallel and indicate northeast-southwest extensional direction at the restored position (figs. 15C and D). At a given scale, the development of extensional faulting or boudinage inside a stratigraphic succession depend on their lithological features, which control the mechanical properties of the multilayer. In the Porma Mélange, boudinage develops wherever the thickness ratio of brittle layer and ductile layer is small (figs. 7 and 10), in accordance with theoretical and experimental results (Kidan and Cosgrove, 1996; Mandal and others, 2000). If the proportion and relative thickness of the competent beds is larger in the multilayer, then staircase normal faults and related fault-bend folds are formed, as in figure 15.

Pre-Carboniferous preorogenic sequences provide the biggest blocks, irrespective of whether the rocks are siliciclastic or carbonatic, which can be due to the fact that both of them were well lithified. The blocks are in some cases rocks derived from one single formation (quartzites from the Ordovician Barrios Formation, sandstones from the Cambrian Herrería Formation or limestones from the Carboniferous Barcaliente or Valdeteja Formations). Some other times they are composed of two or more formations, for example quartzites from the Barrios Formation and limestones from the Barcaliente Formation or limestones from Barcaliente and Valdeteja formations (fig. 4). These preorogenic blocks do not occur as boudins but as exotic blocks included within the synorogenic lutites. Their emplacement process will be discussed further.

Shear Zones

In the lower part of the Porma Mélange, narrow non-coaxial shear zones developed at the mélange matrix, up to 2 meters thick, have been found, experiencing the

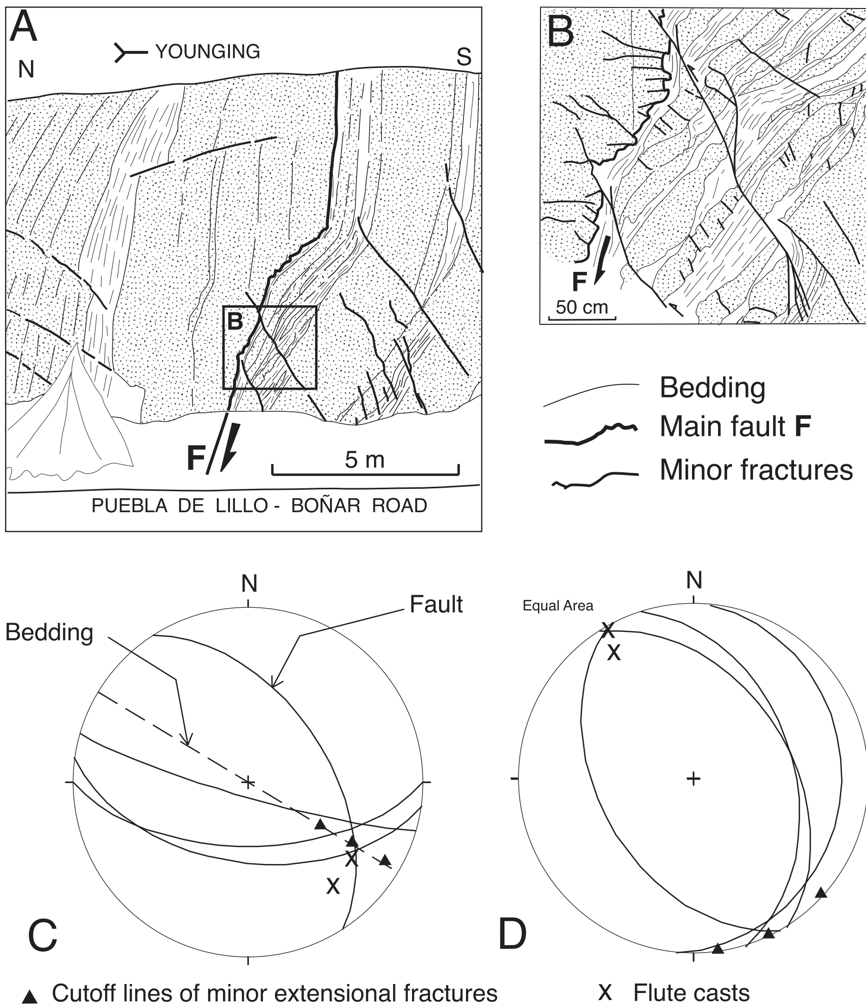

Fig. 15. (A) Outcrop sketch along the Porma reservoir road, showing the geometry of the extensional faults. Location in figure 4. (B) Detail of the main fault surface (F) and minor faults. (C) Stereographic plot of the structural elements in section (A). (D) Restoration of the structural elements of plot (C) if the bedding is rotated to its initial horizontal attitude.

highest shear strains (fig. 10). Outcrops are scarce in this area and therefore reconstructing the overall traces of the shear zones is not possible.

Figures 13 and 16 show the internal structure of two instances of these shear zones. In the shear zone located on the right of figure 13 three parts can be differentiated: the upper and lower part consist of anastomosing, north-dipping shear surfaces parallel to shear zone boundaries (C-type) with down-dip striations. In the middle part, the cleavage (S_1) was folded and a strong secondary cleavage (S_2) parallel to C surfaces developed, with some microfolds preserved within microlithons. This middle band is darker than its adjacent parts. Inside the shear zone there are also centimetric fragments from harder rocks (sandstones and limestones) deflecting the cleavage, with a range of shapes like the boudins described above. However, in this case rhomboid blocks are oriented as a σ-type object (Passchier and Simpson, 1986) of the shear zones, so they seem to have rotated to reach that attitude.

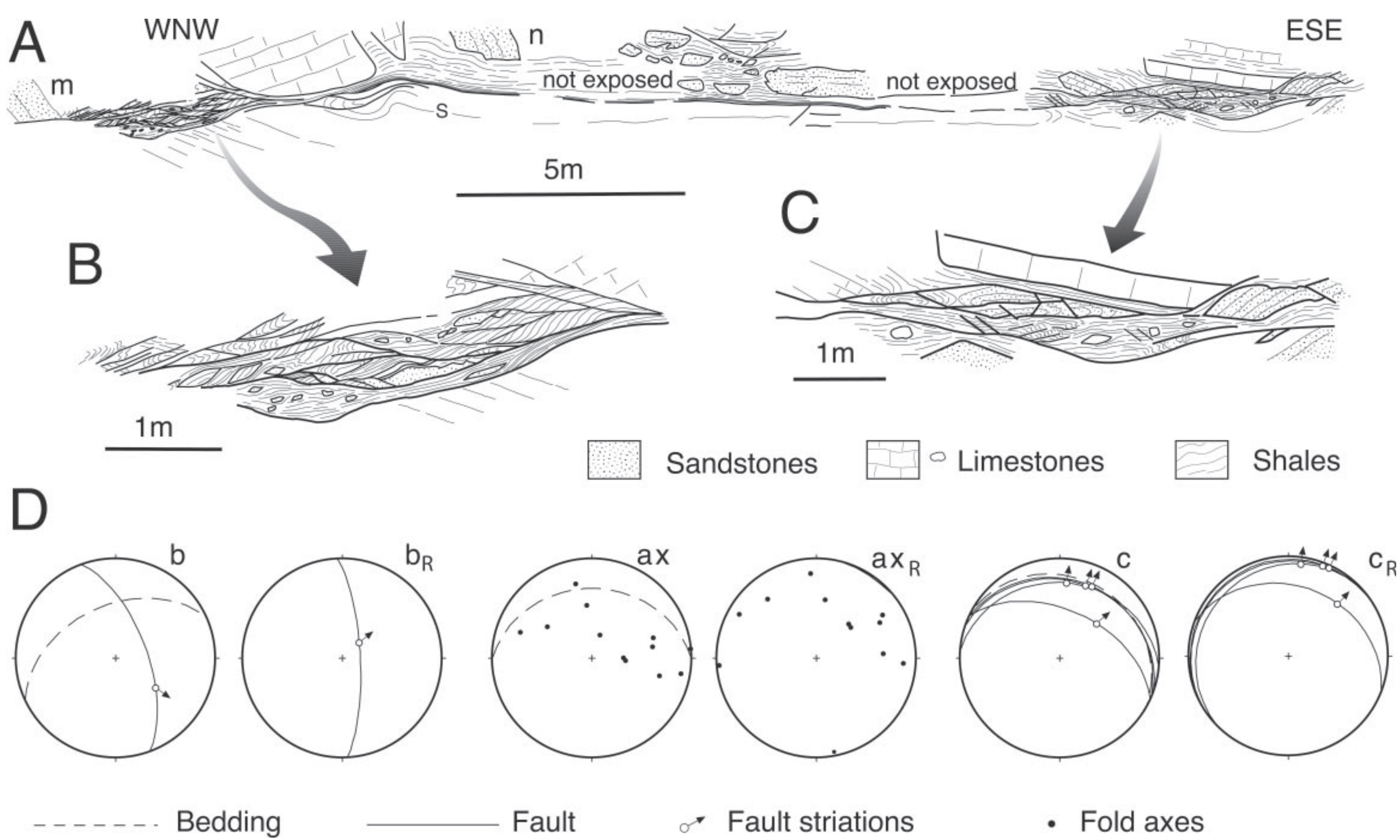

Fig. 16. (A) Shear zone in the basal part of the Porma Mélange. (B) and (C) Close-up views of (A). (D) Left and right: stereoplots of faults in figures 16B and C. Center: stereoplots of fold axes of figure 16A. Plots with subscript (R) in their labels show the attitude of the structural elements after restoration of the bedding.

The shear zone of figure 16 consists of a highly deformed dark band, some 10 centimeters thick, overlying a fault with ramp-flat geometry. The shear zone is also slightly folded and broadens in the sectors where the fault has rough geometry (the two ends of fig. 16). At the western end (fig. 16B), above the more deformed sector, anastomosing C and C′ surfaces are found separating domains either with shortened or extended cleavage; the eastern end (fig. 16C) shows cleavage flexures oblique to shear zone boundaries (C′-type, dipping towards the right and to the left) in the lower zone, more strongly deformed, as well as asymmetric folds. Above it, eye-shaped folds developed. Several stiff fragments from sandstones and limestones, the ones with rhomboid shape oriented as σ-type objects, also occur within the shear zone. The blocks above the shear zone are mainly arranged in parallel with that zone, except for two sandstone blocks (m and n in fig. 16) that have undergone some rotation, which, in the Porma Mélange, is unusual outside the shear zones. The stronger rotation of these blocks as compared to the rest must have been due to their more equant shape. At low angle to the direction of simple shear, the shorter inclusions rotate faster than the elongate inclusions, a marker line being the slowest and the equant inclusion the fastest (Gosh and Ramberg, 1976). A similar relationship has been documented in the Shimanto belt (Cowan, 1990). The sense of relative motion has been determined from C and C′shear bands, striations and σ−type objects, which are indicative of a dextral sense.

Figures 13C and 16D show projections of the different structural elements of these shear zones. These faults and shear zones, now with dextral-reverse movement sense, become normal (shear zones of fig. 13) or horizontal (shear zone of fig. 16) if bedding is restored to the horizontal attitude. In the shear zone located on the right in figure 13, constant orientation of fold axes, perpendicular to the striations, supports the idea that they are perpendicular to the transport or shear directions (Woodcock, 1976). Hinge lines in the shear zone of figure 16 are roughly distributed about the great circle defined by the average cleavage orientation. These variable hinge-line orientations and asymmetry are usually interpreted to reflect the results of progressive rotation of initial hinge lines into the shear direction. Figure 16C presents close sheath folds with the cone axis parallel to the slickenfibres lineation. Theoretical and experimental modeling of fold axes rotation within a body undergoing progressive bulk simple shear shows that significant alignment of axes near the shear direction does not occur below shear strains of 10 to 20 (Skjernaa, 1980; Cobbold and Quinquis, 1980), which may indicate minimum strain in this shear zone. Any additional component of extension in the intermediate strain direction should decrease the amount of rotation for a given shear strain. The outcrop section of figure 16 is markedly oblique to the displacement vector. The development of conjugate C′-type shear bands may imply the presence of simple shear perhaps combined with extension longitudinal to the shear zone.

THE ORIGIN OF PORMA MÉLANGE: PROGRESSIVE UNROOFING OF THE NAPPE TOE BY GRAVITY COLLAPSE

As indicated in the introduction, a strong controversy arises around the interpretation of the origin of mélanges, particularly with regard to whether stratal disruption was produced in thrust-related shear zones or as a result of gravity collapse. The Porma Mélange provides the following strong arguments supporting collapse spreading and against thrust-related shear zone: block provenance, flattening-type ellipsoid and progressive unroofing of the nappe toe inferred from the distribution of blocks ages in the basin.

1) Block Provenance

Mélange occurs beneath the Forcada Nappe; if the mélange unit were a Forcada Thrust-related shear zone, the mélange blocks would have detached from the base of the Forcada Nappe; however, block lithologies can be correlated with formations of the overlying Bodón Nappe, mainly with its upper part. The presence of quartzites from the Ordovician Barrios Formation, sandstones from the Cambrian Herrería Formation or limestones from the Carboniferous Valdeteja Formation, allow them to be related to the Bodón Nappe (figs. 4 and 5) because these formations do not occur in the Forcada Nappe. Blocks derived from the Pennsylvanian succession may also be part of the Bodón Nappe. Many of them consist of limestones from shallow-water areas containing large foraminifera, and algae; that are currently visible in the Bodón Nappe. In addition, the presence of previously folded rock blocks in the mélange supports their deriving from advancing nappes rather than having derived from the foreland basin.

2) Flattening-type Ellipsoid

A large-scale geological setting compatible with extension in two directions, vertical shortening and horizontal elongations is a laterally unconfined gravitational collapse and spreading. Also, the maximum shortening is perpendicular to the bedding, and it seems reasonable that the beds, not yet well lithified, were horizontal at the time when the faults formed. Such features favor collapse rather than the fault zone hypothesis, where plane strain with negligible elongations parallel to orogenic trends can be expected. The existence of shear zones at the base with high degrees of non-coaxiality and different transport directions is consistent with the gravitational displacement of the mélange. We propose a piedmont glacier or an ice cap as an appropriate analogue for deformation of the Porma Mélange, in the same way as Cowan (1982) did for the deformation of Franciscan sediments, where the strain values are much smaller than in the Porma Mélange. Ice and rock collapse and spread laterally under their own weight. In the upper part of the glacier profile there is a domain of coaxial strain (pure shear) accommodating vertical collapse and, progressively, changes to non-coaxial in a basal zone characterized by high shear strains. This probably reflects frictional resistance to sliding (Hooke and Huddleston, 1978). A change from extensional structures in the upper part of large mass wasting deposits to heterogeneous simple shear in the lower part also has been reported in ancient submarine slides (Lucente and Pini, 2003).

Although the overall strain is of flattening type, at a smaller scale the strain is heterogeneous, with folds occurring at very particular sectors. Hence microfolds only occur in simple shear zones (figs. 13 and 16), and may have been caused by the boudin's irregularities or the fault's non planar surfaces (fig. 16). Some other larger folds, such as the one deduced from the existence of opposite polarities in figure 7, occur only exceptionally and may have originated from an irregular bottom or at the slump's front, as it happens with glaciers deformation.

3) Progressive Unroofing of the Nappe Toe

The Porma Mélange blocks are not distributed at random, but some parts of the mélange differ from others with respect to the type of blocks they present. Each sector is characterized by prevalent types of blocks. The age distribution of the different blocks visible on 1:50.000 maps is shown in figure 17. The upper part of the figure shows the first occurrence of blocks of a certain age, although the same rock types reappear more to the northeast. The proportion and abundance of blocks of a determined age (Carboniferous and pre-Carboniferous) is indicated at the bottom. The blocks of the rear part of the basin, located to the southwest of Armada and Pallide klippes, consist mainly of Carboniferous limestones and graywackes. The proportion of pre-Carboniferous blocks there only reaches up to 4 percent. In the area located northeast of these klippes, the ratio of pre-Carboniferous increases up to 29 percent. Taking into account the transport direction of the nappes from southwest to northeast,

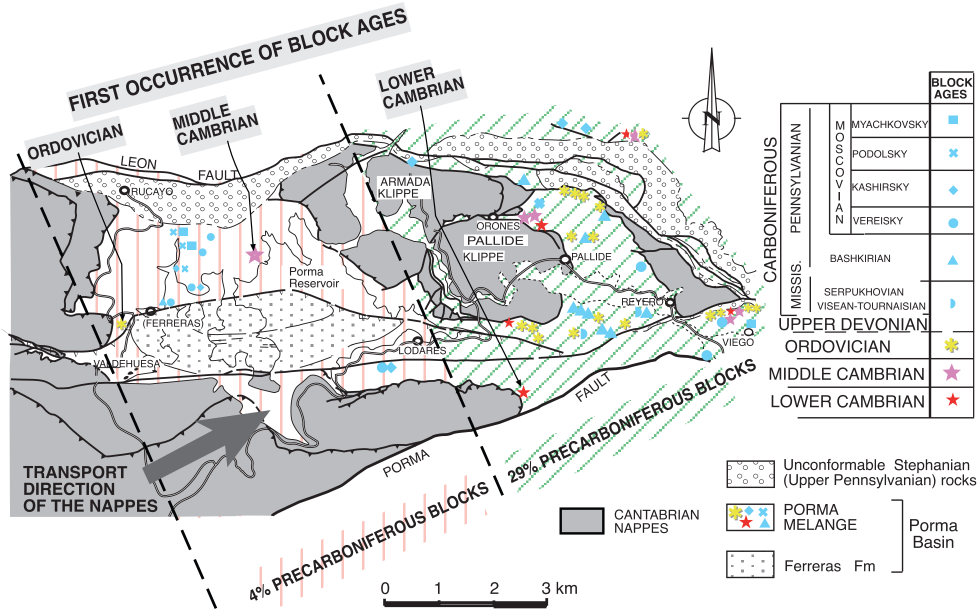

Fig. 17. Distribution of blocks of a given age in the Porma Mélange. Top: first occurrence of blocks ages. Bottom: frequency distribution of blocks ages.

this block distribution suggests early collapse of the upper part of the nappe toe. This mechanism implies progressive development of normal faults with gradually lower (progressive unroofing) or more back (scarp retreat) dècollement levels (fig. 18). At an early stage of sliding, Pennsylvanian series have been important as the provenance of the Porma Mélange; the pre-Carboniferous succession has played an increasingly important role as the source of rocks for blocks at later stages. In case of a shear zone associated to the thrust, the blocks should have been detached from the nappe bottom in an opposite order: first the basal blocks and then the upper blocks, and thus their distribution would also be opposite.

The large blocks of previously folded strata need special consideration. Bedding within the blocks is tightly folded and this folding pre-dates extensional structures and emplacement of the blocks (figs. 10 and 14). In the Cantabrian Zone, hectometric scale folds are always associated to frontal hangingwall thrust ramps (Julivert and Arboleya, 1984; Alonso, 1987; Alvarez Marrón and Pérez-Estaún, 1988); assuming that they are folds of this kind, they are only slightly rotated, like the rest of the blocks, as their axial traces remain normal to northeast transport direction (fig. 10). The presence of these blocks containing previous folds suggests, thus, the destruction of the frontal hangingwall ramp (figs. 18A and B).

EMPLACEMENT PROCESSES: THE MEANING OF "NATIVE" AND "EXOTIC" BLOCKS

The different emplacement mechanisms involved in the development of the Porma Mélange depending on the degree of lithification are shown in figure 19. The boudinaged sequence of Pennsylvanian age originated from gravitational spreading of a succession of interbedded competent (lithified) and incompetent (not well-lithified) rocks involving great internal deformation. A few blocks were dislodged from pre-Upper Carboniferous formations, in which all the rocks were well lithified. These pre-Carboniferous blocks incorporated into the mélange as individual slip blocks with

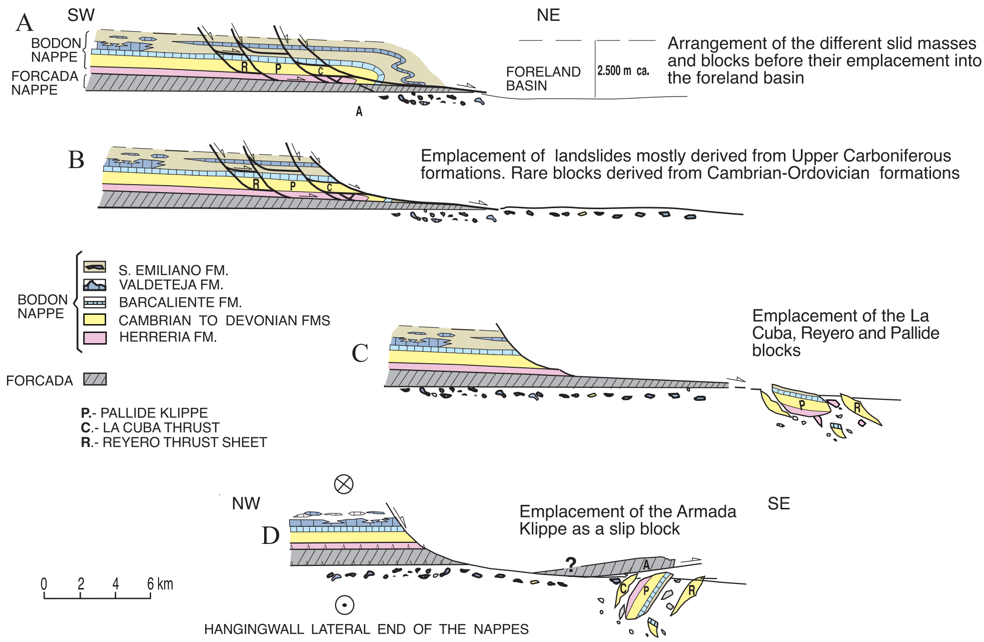

Fig. 18. Idealized initial arrangement and emplacement sequence of the material slid into the Porma Basin.

minor internal deformation, forming the bigger blocks (fig. 4). Such blocks are traditionally known as "exotic". Nevertheless, the boudinaged sequence is also considered exotic here with regard to the basin. In fact, the Pennsylvanian limestones were deposited in shallow marine waters and, therefore, cannot have deposited ahead of a 3 kilometers thick submarine nappe like the Forcada-Bodón Nappe Pile (fig. 18).

Collapse spreading at the nappe toe should be favored where sediments were incompletely lithified, that is where Pennsylvanian formations are involved, giving rise to the greater volume of slumped deposits, which moved on basal shear surfaces. The high ductility is evidenced both by the bedding-parallel cleavage and by hydroplastic fractures, both of which are regionally restricted to the Porma Mélange, as they do not occur either in the underlying formation of the Porma Basin (Ferreras Formation) or in the Bodón and Forcada Nappes. This cannot be explained by lithological reasons, for both nappes exhibit thick formations with a high proportion of shales. The very high strain of the mélange (over 300%) can also be explained assuming poorly lithified

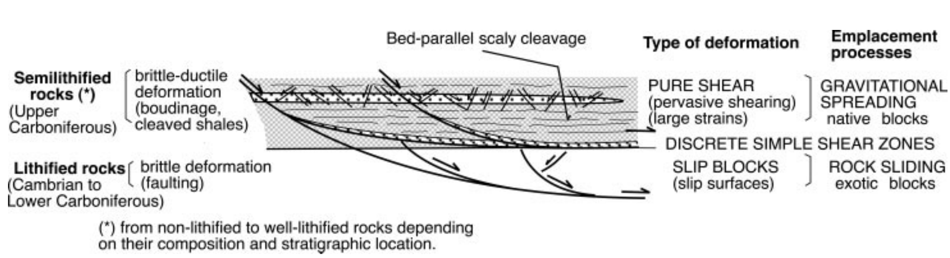

Fig. 19. The different processes involved in the emplacement of the Porma Mélange depending on the sediments degree of lithification.

sediments, with a ductility level that is exceptionally high in the Variscan Chain of northwest Spain, and even more so at its foreland (Cantabrian Zone).

Collapse of the preorogenic rocks was much less common, due to the fact that the shear strength was larger for older rocks, already lithified.

Progressive unroofing of the Bodón Nappe implies several slumps and, therefore, the mélange stratigraphy should probably include a series of amalgamated landslides. Owing to the poor quality of the outcrops, it is not clear through structural analysis how many successive slumps were involved in the development of the Porma Mélange. Nevertheless, the problem can be studied from a different perspective. The piling up of different slumps may cause some ages to repeat due to retrogressive slumping or inverted chronostratigraphy in the basin resulting from the unroofing process in the nappe toe.

DISCUSSION ON EMPLACEMENT PROCESS OF THE MAJOR NAPPE FRAGMENTS: TECTONIC "KLIPPES" OR SLIPPED BLOCKS?

Some nappe fragments or "exotic" blocks in the Porma area reach up to several kilometers in size and have traditionally been known as klippes, although their emplacement process has been controversial. The lack of connection between a thrust sheet and an isolated parent rock body may be interpreted either as remnant of a previously continuous thrust sheet, that is to say, a tectonic klippe, or as a megablock slipped down into the basin from an approaching nappe. These gravity slipped blocks have been known in the literature as "diverticules" (Lugeon, 1943), "klippes sédimentaires" (Lamare, 1947) and "geitklippen" (Görler and Reutter, 1968).

The relationships between the blocks and the surrounding rocks may help differentiate the emplacement process followed: tectonic klippes will settle on the sediments of the foreland basin, while slipped blocks will usually remain included as part of these sediments or of some other slipped materials. Where the block's size is from small to moderate, and if they are well-exposed, their relation with the matrix can normally be determined. However, when blocks are large, it is more difficult to determine whether they overlie the matrix (klippes) or they are slide blocks or boudins included within it. This is the reason why the interpretation of blocks of kilometric scale has been controversial in some orogens (Rodgers, 1997). Some geologists believe that coherent rock bodies of the Apennines (Page, 1962; Marroni and others, 1998; Marroni and Pandolfi, 2001) and of the Montagne Noire (Engel and others, 1978), measuring sometimes 1 to 10 km in length and breadth, may be gigantic olistoliths.

The geometric relationships between the different giant nappe fragments of the Porma area, that will be described below, make it possible to discuss the processes by which these giant blocks were emplaced in the basin.

Structure of the "Klippes" and their Relation to Underlying Rocks

The first geological maps to record the Armada and Pallide "klippes" (De Sitter, 1962; Rupke, 1965) show confusing relationships between these structures and the Carboniferous rocks around them. In fact, the same Carboniferous rocks were mapped as unconformable and underlying the basal thrusts of the klippes. Lobato (1975), in turn, considered that the boundaries between the klippes and the Carboniferous rocks had to be either thrust surfaces or some other types of faults. Both this author and Heredia (ms, 1991) interpret the klippen as having structural continuity with the Bodón and Forcada Nappes, from which they are currently being isolated due to erosion.

Alberts (ms, 1985), Tromp (ms, 1985) and Nijman and Savage (1989) consider the klippes to be precursory olistholiths or diverticulate thrust sheets from the Bodón and Forcada Nappes transported by means of a gravitational mechanism (Pallide Klippe with southward and Armada with south-west provenance). This interpretation relies especially on the nature of the synorogenic sediments but no structural arguments were used.

The geometric relationship between the Armada and Pallide klippes is shown in figures 3, 4 and 6A. The stratigraphic succession of Pallide is overturned at the contact zone between both klippes while that of Armada is normal although both of them display steep dips (fig. 6A).

In the Armada Klippe the basal thrust displays a hangingwall flat located at the Middle Cambrian Láncara Formation. As for the footwall, the thrust overlies the Porma Mélange, except at the east end of the klippe (figs. 4 and 6A).

In the western part of the Pallide Klippe, the thrust is located at the Lower Cambrian Herrería Formation, climbing eastwards up the stratigraphic succession until it reaches the Carboniferous shales of the San Emiliano Formation.

Apart from the two large klippes of Armada and Pallide, two other major nappe fragments overlie the Porma Mélange (La Cuba and Reyero, figs. 3 and 6A), whose stratigraphic succession correlates to the Bodón Nappe, although, unlike at Bodón, the décollement level of these sheets is the Láncara Formation. The La Cuba Thrust Sheet outcrops in the southwest of the Pallide klippe, both structures having a similar overturned attitude, younging to the east. The stratigraphic succession of the La Cuba Thrust Sheet ends at the Barrios Formation, overlain by a thin band of Upper Carboniferous rocks separating this sheet from the Pallide klippe. The Reyero Thrust Sheet also ends at the Barrios Formation, although in this case the boundary is a reverse fault involving the Stephanian (Upper Pennsylvanian) rocks. The attitude of this klippe is also overturned (fig. 4).

One significant fact regarding the interpretation of the klippes is provided by the overall geometry of their basal thrust surfaces. When restoring the thrust sheet geometry, assuming that the klippes are fragments from the Bodón and Forcada Nappes, the basal thrust between the nappes does not agree with simple geometric rules of thrusting. For instance, the Bodón Thrust cannot have climbed upwards from the Herrería Formation to the San Emiliano Formation at Pallide and then downwards to the Láncara Formation and the Reyero Klippe (see fig. 4) because thrusts usually climb across the stratigraphic succession following the tectonic transport direction, that is, north-eastwards, without further downward movement unless when earlier structures are truncated. Although more complicated kinematic models of thrust propagation could explain the present geometric relation between Pallide and Reyero blocks, these models could not explain the occurrence of exotic blocks of very different sizes, shapes and lithology in this area (fig. 4).

Diverticulation and "Peel off" of Slides

As described above, the blocks of the Porma Mélange become progressively older northeastwards, that is, the nappe transport direction, as a consequence of its progressive unroofing during displacement. Another common feature in slid deposits, with the same or very similar interpretation, is the so-called diverticulation or stratigraphic inversion: higher blocks may contain older rocks than lower blocks (Lugeon, 1943; Kugler, 1953; Rigo de Righi, 1956; Badoux, 1967; Görler, 1967). Both mechanisms imply progressive development of normal faults with gradually lower dècollement levels.

The bulk stratigraphic order of the different "klippes" in the Porma Basin is inverted to that of the Bodón and Forcada Nappes in the southwest sector (fig. 4) (Suárez and others, 1996). That is: i) the Pallide Klippe, which includes the Lower Cambrian Herrería Formation, overlies the La Cuba Thrust Sheet, detaching at the Middle Cambrian limestones of the Láncara Formation; now both blocks are overturned; and ii) the Armada Klippe overlies the Pallide Klippe in a sequence opposite that of the source nappes, Forcada and Bodón (fig. 18D).

Nevertheless, the interpretation of the Armada Klippe may be more debatable, because while Pallide and La Cuba fragments are included within the Porma Mélange (fig. 6A), the Armada Klippe lies over the mélange, by means of a hangingwall flat. It could therefore be a true tectonic klippe, well fitted inside the cross-section (fig. 6A). This arrangement does not rule out a slip block, but its emplacement over the Pallide Klippe can also be interpreted as a result of displacement of the Forcada Nappe, after *sliding of the Pallide block into* the basin. The available field data through microstructural analyses at the basal contact of the Armada Klippe (figs. 20 and 21) indicate a southeast transport direction, that is normal to the transport direction of the nappes, although consistent with the northwest-southeast extension direction and shear sense of some of the basal shear zones of the mélange (fig. 13C). The movement of the Armada block would also explain the south-dipping and overturning attitude of La Cuba, Pallide and Reyero blocks (fig. 18D).

A second argument to support gravitational sliding is the stratigraphic omission or "peel off" (Pedersen, 1987) at the upper part of the slides, as a result of previous normal faults. The omission of a large part of the Barrios Formation and of the whole Barcaliente Formation at La Cuba (figs. 4 and 6A) may be caused by peel off or gravitational tectonic denudation prior to the emplacement of the Pallide block (fig. 18B).

REGIONAL MODEL

The extension in two directions recorded in the Porma Mélange is consistent with gravitational collapse from a nappe toe. The restoration of the extension directions, so as to obtain the orientation they had when they were generated is risky in the case of the Porma Mélange due to the superposition of successive deformations. However, there are two restoration procedures whose results are very similar: rotating the southern limb of the Armada Syncline to a horizontal attitude or rotating the block's

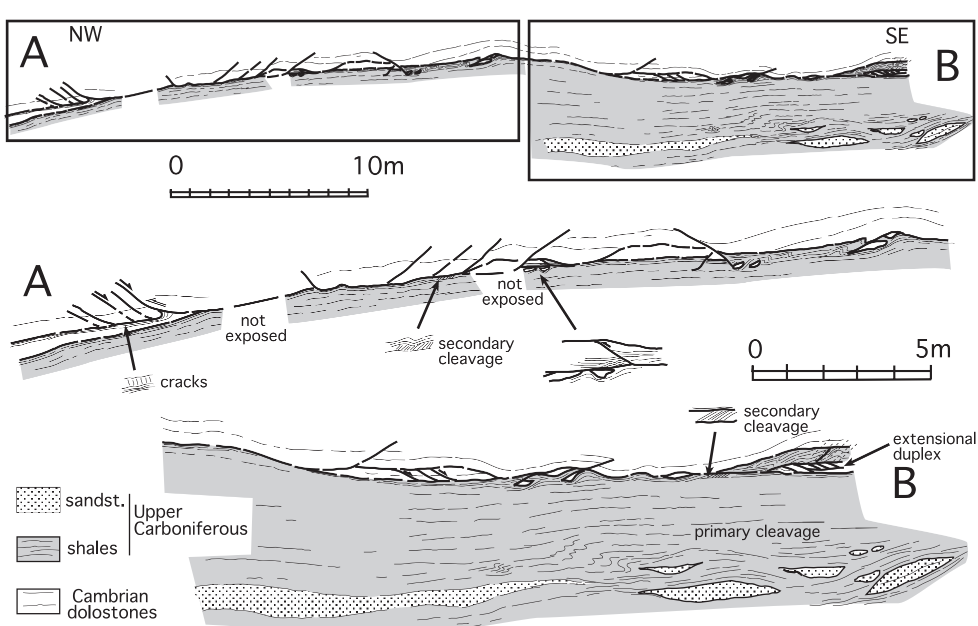

Fig. 20. Minor structures around the basal fault of the Armada klippe.

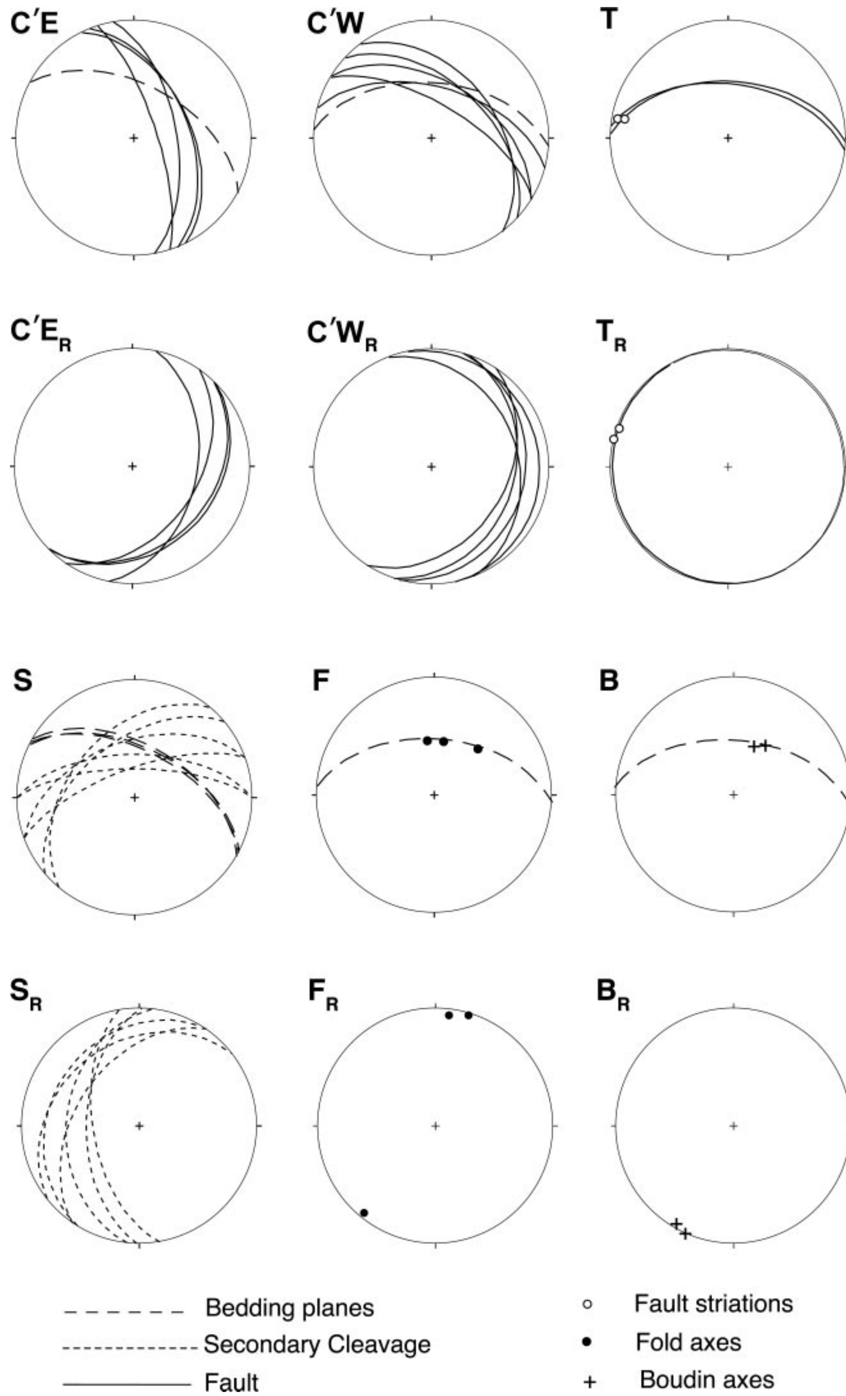

Fig. 21. Stereoplots of structural elements in figure 20. Plots with labels C′E and C′W show extensional faults located at the eastern and western sectors in figure 20. T plot represents the principal fault surface. Plots with subscript (R) in their labels show the attitude of the structural elements after restoration of the bedding.

bedding, assuming that the beds lay horizontally during the extension period. The results are similar because the strikes of the boudins are subparallel to one another and to the general trend of the chaotic formation and they also lie parallel with the bedding of the overlying Armada Klippe or the underlying Ferreras Formation; beds within boudins are commonly upright, dipping steeply northeast (figs. 4, 7, 10 and 11) Randomly oriented blocks are not present in the Porma Mélange and are rarely overturned.

Through restoration a northwest-southeast (lateral) extension direction is obtained with conjugate faults and another one, subperpendicular, with northeast dipping normal faults with a slightly dextral component (figs. 7B, 12 and 13C).

A flattening strain is compatible with gravitational collapse and so is strike-parallel extension with divergent flow. However, more than divergent flow, from which a radial extension pattern would then be expected, the consistent occurrence of extension in two perpendicular directions suggests that the chocolate tablet boudinage could have been controlled by an inherited structure as Ghosh (1988) has shown from analogue experiments. In fact, the two sets of extensional fractures are parallel to frontal and lateral structures related to nappe emplacement. Figure 22 shows an idealized panoramic view of the Porma Basin during the deposition of the Porma Mélange.

Regarding the information recorded from megablocks, the southeast sliding direction of the Armada block (figs. 20 and 21) suggests that gravity collapse could also have taken place at a hangingwall lateral ramp of the nappes moving along a submarine basin (fig. 22).

CONCLUSIONS

The Porma Mélange, located below a nappe stack, in the Variscan foreland of the Iberian Peninsula, provides useful information to understand some well-know features of the block-in matrix deposits called mélanges. Most of the Porma Mélange consists of a boudinaged sequence of Pennsylvanian age, with extension values over 300 percent. The boudins may reach up to hectometric size and are commonly bounded and crossed by two sets of shear fractures causing layer-parallel stretching in two subperpendicular directions (chocolate tablet structure). In the matrix, a weak bedding-parallel

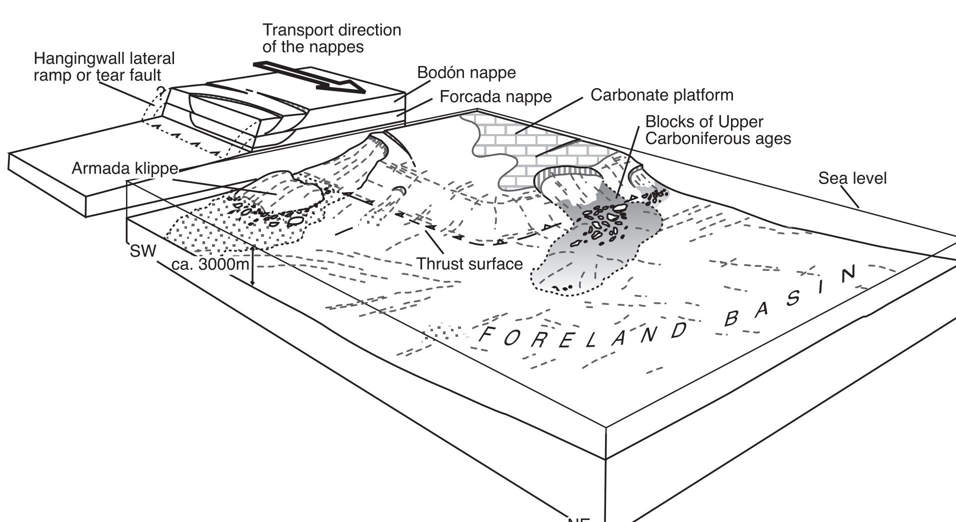

Fig. 22. Idealized panoramic view of the Porma Basin during the deposition of the Porma Mélange.

cleavage evidences layer-perpendicular shortening. The almost complete parallelism between the bedding of equant and elongate boudins suggest a coaxial strain path with the XY plane nearly parallel to the bedding. This boudinaged sequence also contains scattered "exotic" blocks with a range of ages from Lower Cambrian to Lower Carboniferous.

The provenance of the mélange rocks, both of the boudinaged sequence and "exotic" blocks, mainly from the upper part of the nappe stack, and the flattening-type ellipsoid are arguments supporting gravity slides from moving nappes and against a thrust-related shear zone, a classical controversy regarding the origin of mélanges. Statistical distribution of blocks ages in the Porma Basin where blocks are progressively older in the nappe transport sense, suggests early collapse of the upper part of the nappe pile and progressive unroofing through subsequent submarine slides.

The internal structure and size of the mélange blocks may be related to the degree of lithification of the rocks, since it depends on their age and composition. The boudinaged sequence derives from the semilithified Pennsylvanian synorogenic sequence, a shallow marine succession located at the upper part of the highest nappe. Graywacke-shale boudins rarely exceed metric scale and display closely centimetric spaced faults in their litharenitic bases that disappear and pass to ductile deformation in the shaly upper part of the beds. Limestone-marl multilayer boudins reach up to hectometric size. Limestone boudins show lesser internal deformation than wacke boudins; their internal faults, if there are any, are widely spaced and cut across the whole boudin without noticeable displacement changes recording a more brittle behavior. This different behavior may be attributed to faster lithification of limestone compared with sandstone (Tucker, 1991). PreCarboniferous preorogenic sequences provide the biggest blocks, irrespective of whether the rocks are siliciclastic or calcareous, probably because both of them were well lithified, and located at the lower part of the nappe stack.

From the structural analysis of the Porma blocks it can be concluded that other features of the mélanges, such as the occurrence of the so-called "native" and "exotic" blocks may be explained in terms of suitability for sliding in the front of the moving nappes. The larger amount of Pennsylvanian rocks (boudinaged sequence) in the Porma Mélange, as compared to the older preorogenic rocks, can be attributed to the different degree of lithification of the materials located at the nappe toe and potentially collapsible by gravitational forces. Collapse spreading should be favored where sediments were incompletely lithified, that is where synorogenic formations were involved, giving rise to the greater volume of slumped deposits. The high ductility evidenced both by the bedding-parallel cleavage and high strain of the boudinaged sequence (over 300%) can also be explained assuming poorly lithified sediments. Collapse of the preorogenic rocks was much less common, due to the fact that shearing strength of the material was bigger for older lithified rocks. These preorogenic blocks came into the basin as individual "exotic" slip blocks but, in fact, the source of all the mélange rocks (boudins or "native" blocks and "exotic" blocks) can be found outside the basin, mainly deriving from the upper part of the nappe stack. So, boudins of the Porma Mélange are also considered exotic here with regard to the basin.

In the lower part of the boudinaged sequence of the Porma Mélange narrow non-coaxial shear zones have been found, experiencing the highest shear strains, which is reasonable to explain its gravitational displacement. The fact that these non-coaxial shear zones have different transport directions is consistent with the flattening strain in the upper part of the sequence.

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