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Paleogeographic inversion resulting from large out of sequence breaching thrusts: The León Fault (Cantabrian Zone, NW Iberia). A new picture of the external Variscan Thrust Belt in the Ibero-Armorican Arc

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ABSTRACT

Out of sequence breaching thrusts may give rise to duplication of a former thrust stack in map view in the same manner that stratigraphic units are repeated by initial thrusts. In this way, large breaching thrusts may put an initial paleogeographic pattern out of order, producing apparent paleogeographic inversions at regional scale. The León Fault, an orogen-scale fault located in the Variscan foreland fold-thrust belt of the Iberian Peninsula, known as the Cantabrian Zone, has caused much controversy in the understanding of Iberian Paleozoic tectonics. The León Fault displays all the features of a breaching thrust and from this interpretation a simple paleogeographic pattern results, once both breaching and former thrusts are restored, in contrasts with previously reported paleogeographic models. This approach implies a redefinition of the geological provinces of the Cantabrian Zone, since some major nappes of that zone, so far considered as different tectonic units, are reinterpreted as one single unit repeated by the León Thrust. It also has implications in discriminating between the various kinematic models proposed for the larger Ibero-Armorican Arc, favouring a late bending of an initial linear belt instead of a progressive change in transport direction during nappe emplacement. Finally, the paleogeographic inversion caused by the León breaching Thrust is compared to other orogen-scale paleogeographic inversions associated with antiformal stacks, such as the preAlps with respect to the Helvetic Nappes, and the Ligurian-Tuscan domains in the Apennines.

KEYWORDS **Variscan belt. Ibero-Armorican Arc. Cantabrian Zone. Breaching thrusts. Out of sequence thrusting. Paleogeography.**

INTRODUCTION

Thrusts in the foreland of orogenic belts are commonly arranged as hinterland dipping imbricate thrust fans, causing shortening of the preorogenic basin. In the absence of back-thrusts, footwall rocks of these imbricate thrust sheets are, from a paleogeographic point of view, closer to the foreland than the hanging wall rocks (Fig. 1A, B). Only when tectonic windows or klippes result from erosion, paleogeographic inversions on geological maps or sections are observed (Fig. 1A, B, C_1). A well-known example of outstanding paleogeographic inversion occurs in the external Alps, where the pre-Alpine Klippe (Penninic Domain) is located ahead of the more external Helvetic nappes.

When thrust systems show two different detachment levels, the thrusts branching from a lower flat may link into a higher level giving rise to a duplex (Boyer and Elliot, 1982*)*, or cutting across it (Coward 1980; Butler and Coward, 1984), in which case they are called "breaching thrusts" (Butler, 1987). At higher structural levels, a breaching thrust may appear as a hindward sequence or "out-of-sequence" thrust (Morley, 1988). Breaching thrusts also produce paleogeographic inversions, because unlike in the imbricate thrusts mentioned above, the hanging wall rocks are, from the paleogeographic viewpoint, closer to the craton than those of the footwall (Fig. 1A, B, C_2). In fact, breaching thrusts give rise to particular types of tectonic windows more difficult to recognize than the common ones, because their leading edges are hinterland-dipping thrusts, instead of facing-down folded thrusts as in ordinary tectonic windows (Fig. 1). However, other distinctive features described by Butler (1987) allow us to recognize breaching thrusts. For example, the same breaching thrust may alternatively carry older rocks on younger rocks or vice-versa (Fig. 2A). When the displacement of a breaching thrust is greater than the thickness of previous thrust sheets, it can give rise to duplication of former thrust stacks in the same way that stratigraphic successions are repeated by initial thrusts (Fig. 2B). In spite of breaching thrusts truncate former thrusts and their related folds, they may display characteristics similar to those of the initial thrusts, such as the development of flat and ramp geometries and thrust-related folds, particularly in their root zones where they propagate into undeformed layers (Fig. 2).

In this paper, the León Fault, one of the longest and most controversial in the foreland of the Variscan Chain of NW Iberia (the Cantabrian Zone), is explained as a "breaching thrust", which has implications for regional and orogen-scale geology. This new interpretation has significant implications with respect to the identification of thrust units and thrust sequences, as well as on the paleogeographic reconstruction of both the pre- and syn-orogenic basins of the Cantabrian Zone, leading to new geological domains. The new model also sheds light in differentiating between the various rotational models proposed to explain the origin of the Ibero-Armorican Arc.

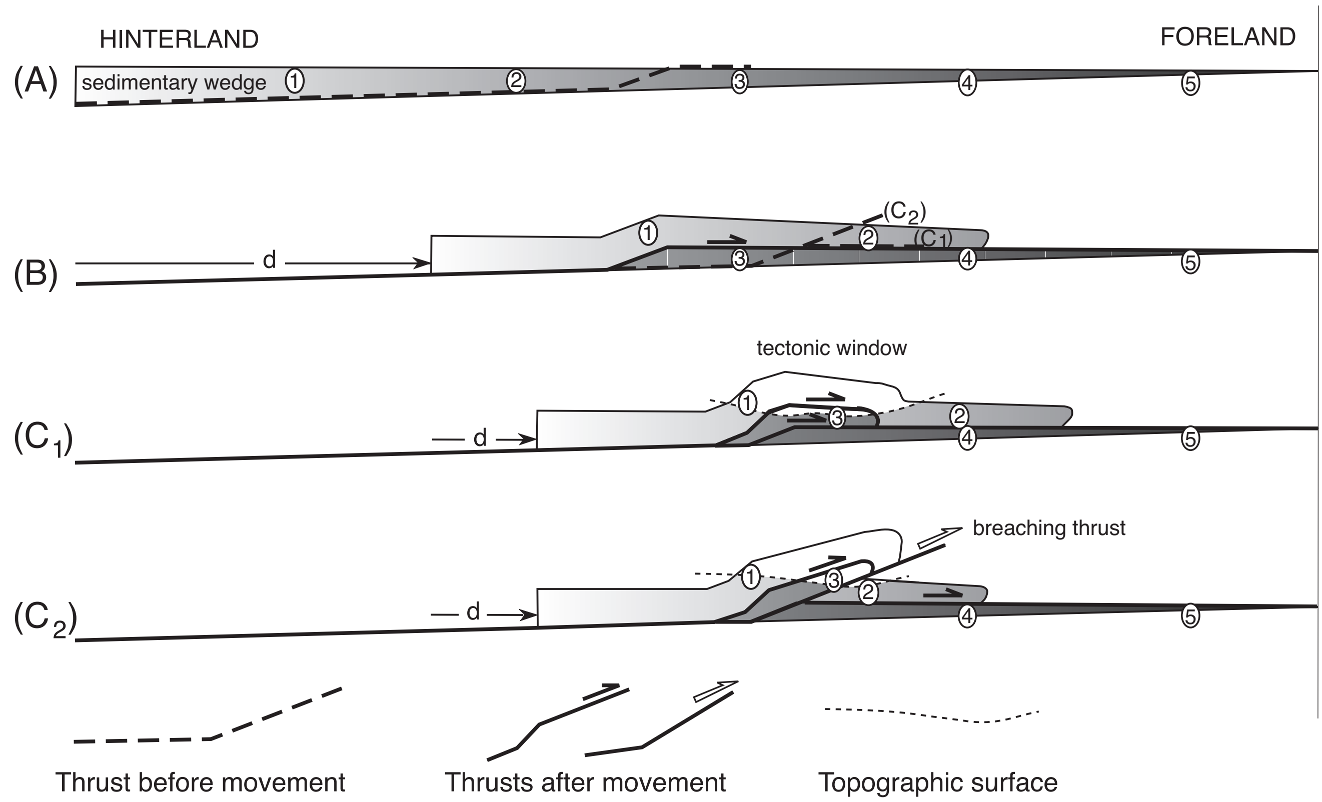

FIGURE 1 | **Paleogeographic inversion as a result of C_1) tectonic window, C_2) breaching thrust. Notice that at the topographic surface, the original order of the paleogeographic locations 2 and 3 in A) become inverted as a result of thrusting in C_1 and C_2. d: thrust sheet displacement.**

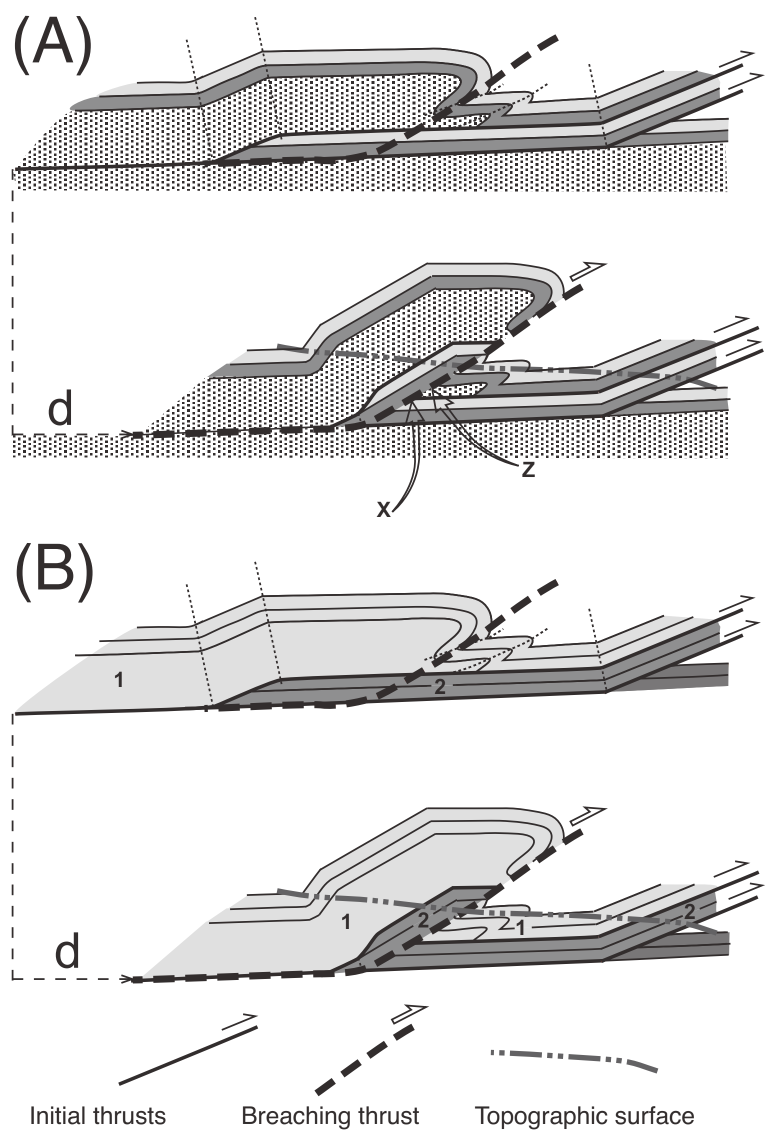

FIGURE 2 **A) An out of sequence breaching thrust can carry younger beds on older ones (point Z) or vice-versa (point X). Based on Butler (1987). B) The same breaching thrust gives rise to duplication of a former thrust stack composed of thrust sheets 1 and 2. d: breaching thrust displacement.**

GEOLOGIC SETTING AND HISTORICAL BACKGROUND

The Cantabrian Zone constitutes the core of the Ibero-Armorican Arc and is the external part of the Variscan Orogen in the NW Iberian Peninsula (Lotze 1945) (Fig. 3). Structurally, it is characterized by thin-skinned tectonics with a transport direction towards the core of the arc (De Sitter, 1962; Julivert, 1971a; Pérez-Estaún et al., 1988) (Figs. 4 and 5). The origin of the arcuate shape has been controversial, its curvature being attributed either to rotational movement of the nappes (Julivert and Arboleya, 1984, a and b; Pérez-Estaún et al., 1988), to late bending of a linear primitive belt (Ries and Schackleton, 1976; Bonhommet et al, 1981; Stewart, 1995; Van der Voo et al, 1997; Weil et al. 2000; Kollmeier et al. 2000; Gutiérrez Alonso et al., 2004; Weil, 2006) or to a combination of both processes (Perroud, 1986; Hirt et al. 1992).

During Alpine orogenesis, the Cantabrian Zone was uplifted and exhumed, as a result of a crustal thrust (Alonso et al., 1996; Gallastegui, 2000), giving rise to the Cantabrian Mountains. However, the Alpine orogeny caused little internal deformation in the uplifted block, in which some Variscan folds and thrusts were slightly reactivated (Pulgar et al., 1999).

Julivert (1967; 1971a) divided the Cantabrian Zone into several geologic domains on the basis of combined stratigraphic and structural features (Fig. 5) and this division has generally been accepted into the literature, sometimes with slight modifications (Pérez-

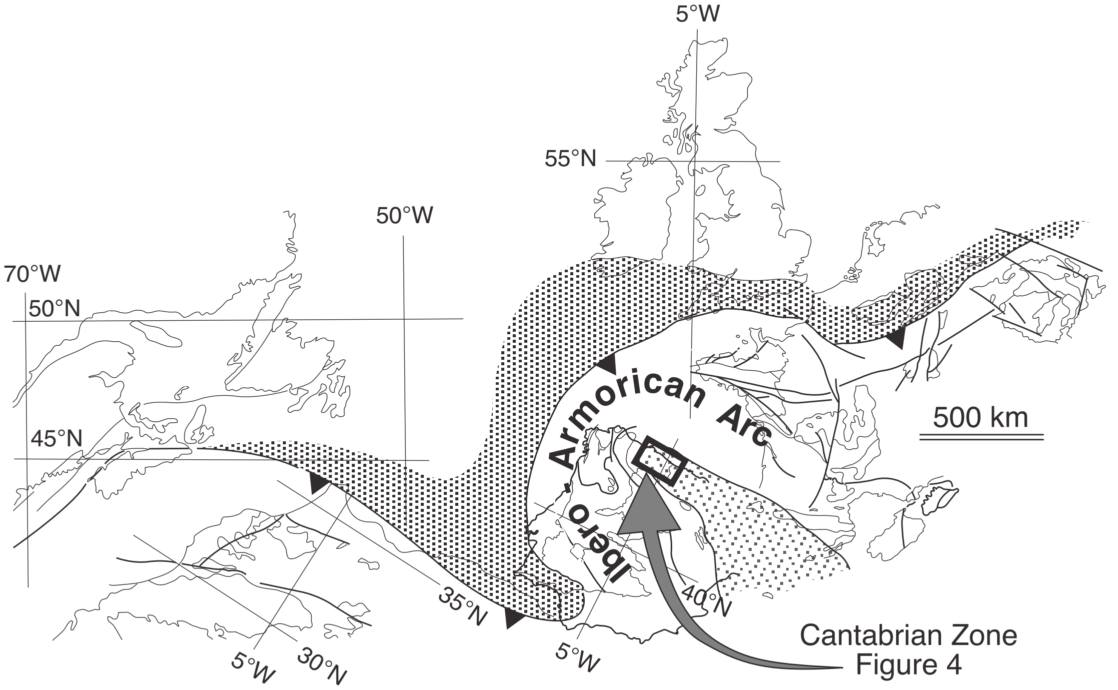

FIGURE 3 | **Location of the Cantabrian Zone within the Variscan Orogen in Western Europe and North America (reconstruction of the Pangea in the area surrounding Iberia after Lefort, 1989). Closed triangles: Variscan Front; heavy dotted: accretionary prism; light dotted: foreland fold-and-thrust belt.**

Estaún et al., 1988; Rodríguez Fernández and Heredia, 1988). The León Fault trends E-W along the boundary that divides several of these provinces. Towards the W, the fault changes to a NW trend, running along the Fold and Nappe Province (Marcos 1968, a, b) (Fig. 5).

De Sitter (1962) first considered the León Fault to be a significant paleogeographic boundary. He interpreted it as an essential fault line that controlled both Devonian and Carboniferous sedimentation and influenced Variscan deformation. This interpretation was followed by other geologists from the Dutch school (e.g. Rupke 1965; Sjerp 1967; Evers 1967, Raven 1983; Savage 1979, Nijman and Savage, 1989).

On the other hand, the geologists of the Oviedo University have considered the León Fault to be a late Variscan strike slip or tear fault of Westphalian to Stephanian age (Marcos, 1968a, b; 1979; Lobato, 1975; Julivert, 1967, 1971b, Julivert et al., 1977; Aller 1986, Alonso, 1987; Rodríguez Fernández and Heredia, 1987, 1988; and Rodríguez Fernández, 1991). They also refer to movements during post-Stephanian times. Other authors, such as Kullmann and Schönenberg (1978) and Heward and Reading (1980), suggested the León Fault is a dextral strike-slip fault responsible for the control of sedimentation during the Carboniferous.

THE INTERPRETATION OF THE LEÓN FAULT AS A BREACHING THRUST

Several arguments supported by old and new mapping data lead to consider the León Fault as a breaching thrust (Figs. 6 to 10):

Structural features of the León Fault and its relationship to other structures

The general cross-sections shown in Figs. 6 and 7, the detailed cross-section of Fig. 8 and the structural map of Fig. 9 illustrate the relationship between the León Fault and other regional structures. The León Fault displays many common features with the former thrusts of the Cantabrian Zone, but differs in some features typical of breaching thrusts.

On the whole, the León Fault displays a map trace and attitude similar to that of the Cantabrian Zone thrusts, although locally it cuts across some of them (Figs. 4, 5, 6A, 7A, 8, and 9). On the southern arm of the Cantabrian Zone, the León Fault trace is sinuous, trending alternatively NE and NW, following the same direction respectively as frontal and lateral structures of the thrust sheets in the southern branch of the Cantabrian Zone (Alonso, 1987; Alonso et al., 1989) (Fig. 9).

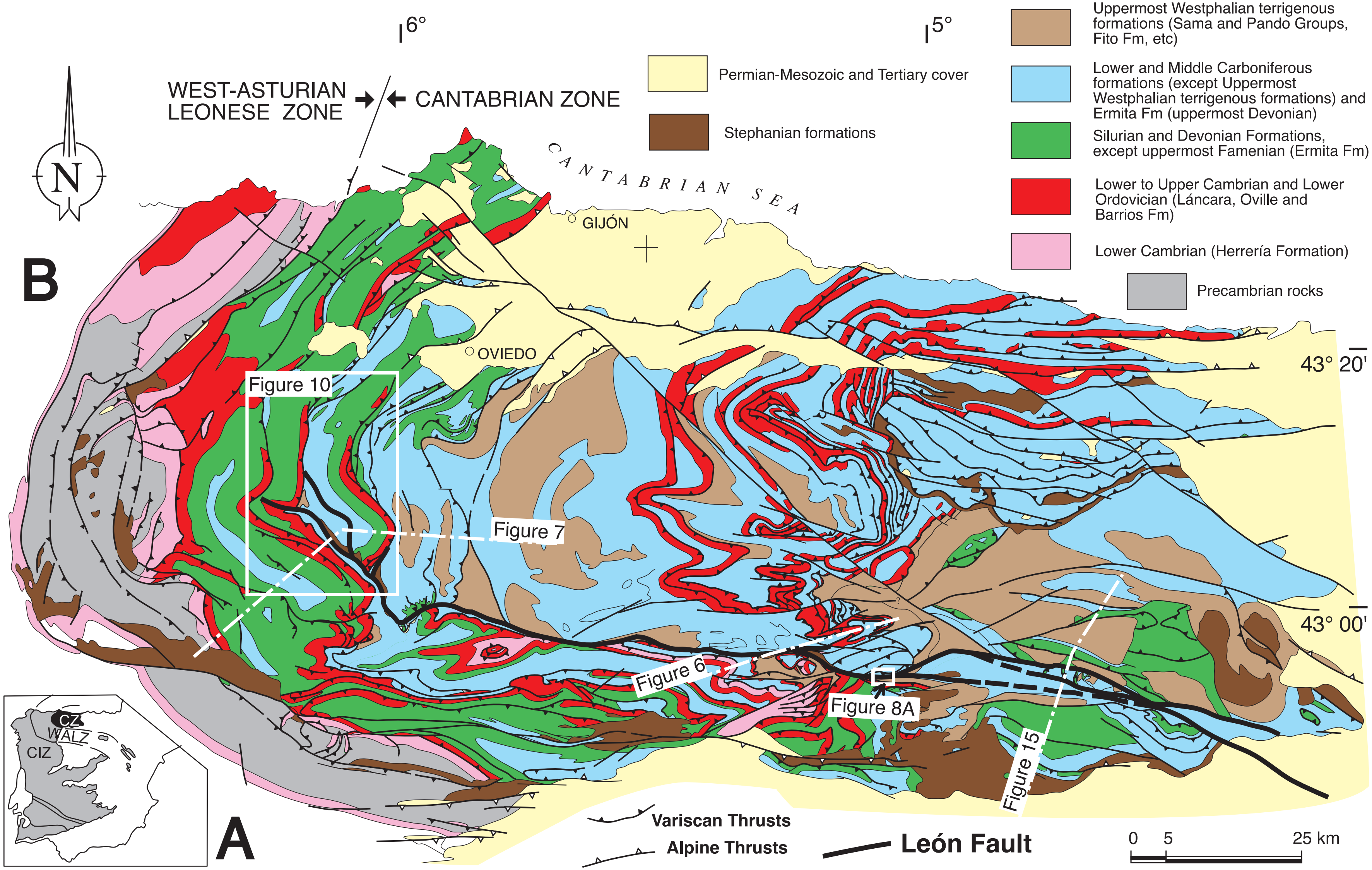

FIGURE 4 | **A) Location of the Cantabrian Zone (CZ) within the Variscan orogen in the Iberian Peninsula. WALZ: Westasturian-Leonese Zone; CIZ: Central Iberian Zone. B) Geological map of the Cantabrian Zone. The León Fault is indicated with a thick line. The trace of the geological sections of Figs. 6, 7, and 15 and the location of the geological maps of Figs. 8 and 10 are shown.**

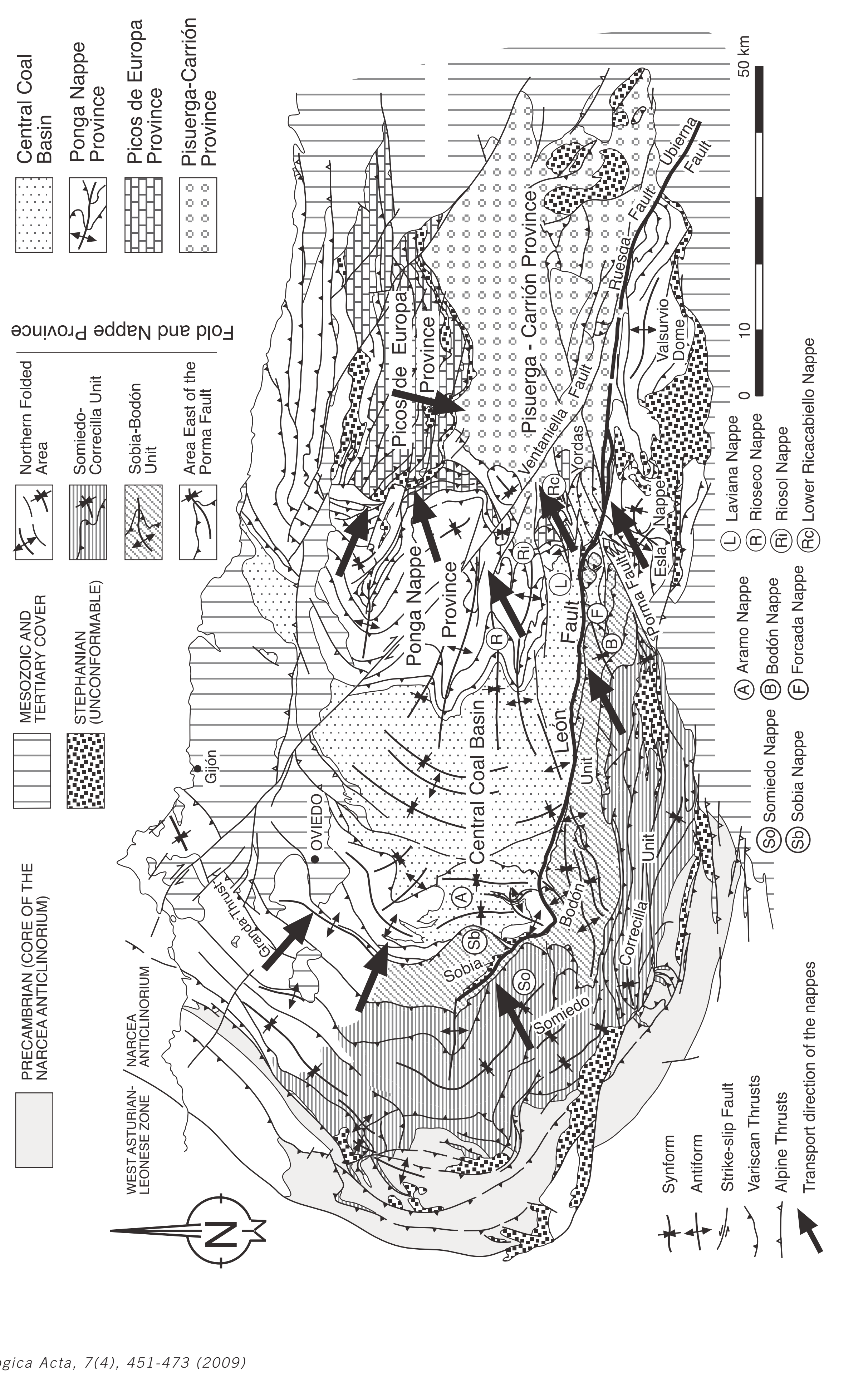

FIGURE 5 | **Structural sketch and division into geological domains of the Cantabrian Zone (Julivert 1971a). Thrusts traces are updated. Arrows indicate the transport direction of the thrusts after Arboleya (1981), Farias (1982), Bastida et al. (1984), Alonso (1987), Alonso et al. (1989), Alvarez Marrón (1989, 1995), Heredia (1991) and Bulnes and Marcos (1994).**

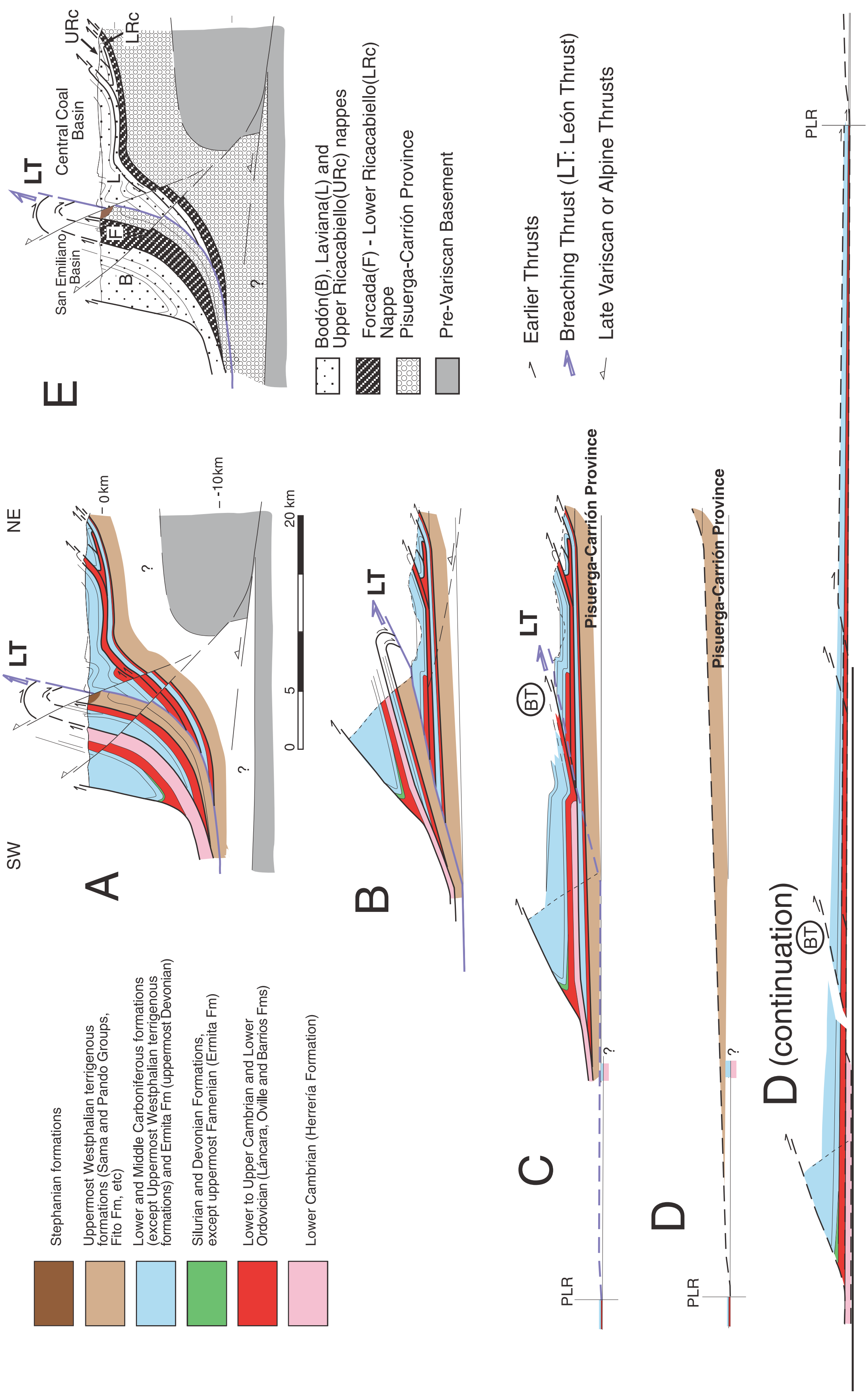

FIGURE 6 | **A) Geological section and B, C, D) sequentially restored sections across the León Fault in the Porma sector. Location and stratigraphic legend in Fig. 4. A) The thickness of the Forcada Nappe is greater in the southern part of section than in the other sections since that section follows the hinge of a lateral fold (see Fig. 4), where incompetent formations are thickened. The other sections show the true thickness of that nappe. BT: tentative location of the foremost part of the Bodón Thrust in C and D stages. E) Names of thrust sheets in simplified section. For this cross-section, constraints were derived from the deep-crustal seismic reflection profiles ESCICANTABRICA 1 and 2 (Pérez-Estaún et al. 1994, Pulgar et al. 1996, Gallastegui et al. 1997).**

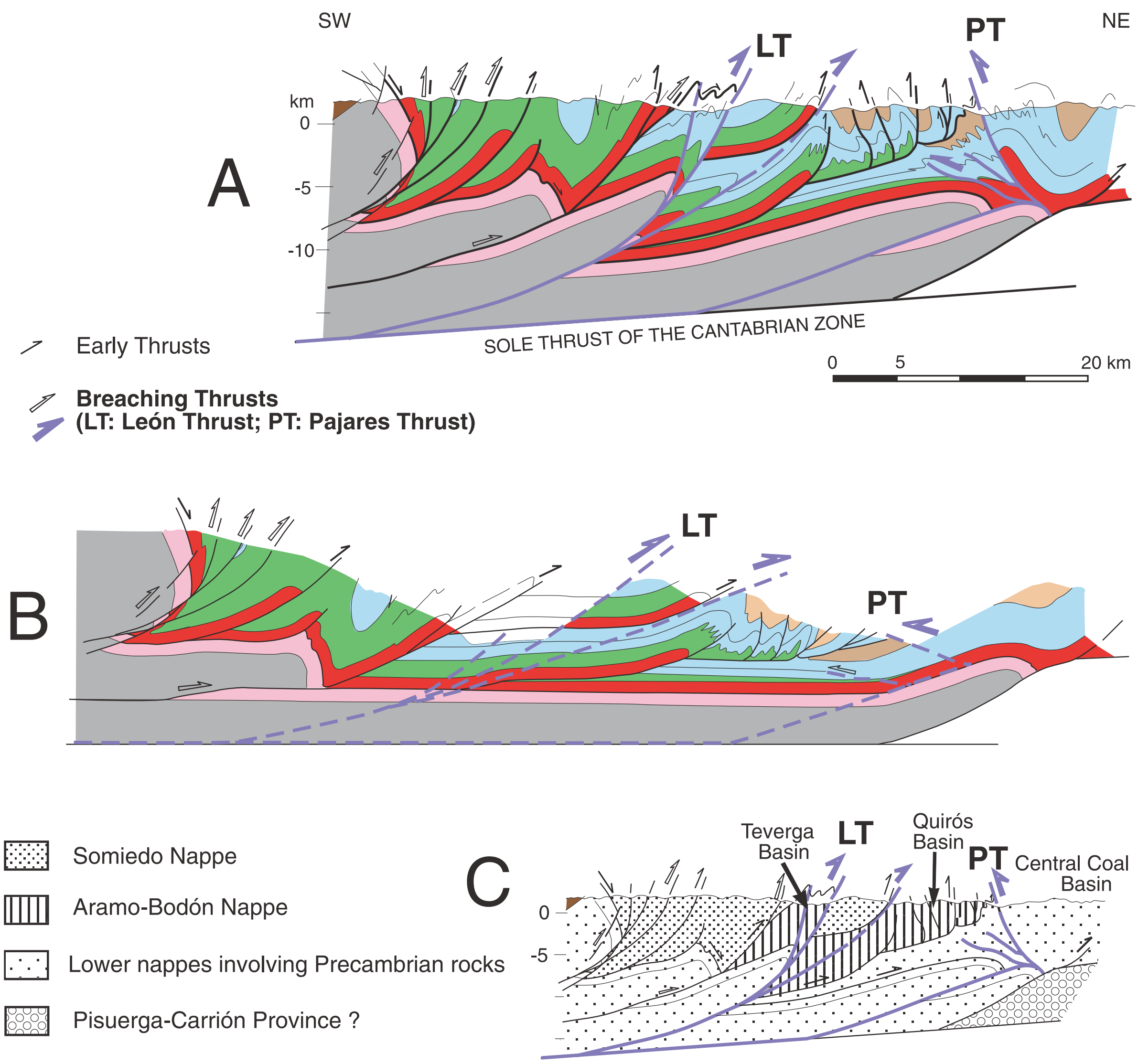

FIGURE 7 | **A) Geological section and B) partially restored section across the León Fault in the Somiedo sector. Location and stratigraphic legend in Fig. 4. C) Names of thrust sheets in simplified section. For this cross-section, constraints were derived from the deep-crustal seismic reflection profile ESCICANTABRICA 1 (Pérez-Estaún et al. 1994).**

With regard to the hangingwall, the fault runs parallel to the Bodón and Forcada thrusts along most of its trace (Figs. 4 and 5). To the West, it cuts across the Bodón Thrust developing hanging wall folds whose axial traces run parallel to the tectonic transport direction. These folds can be interpreted as lateral ramp-related folds. Until now, the León Fault was thought to die out west of the Sobia (Fig. 5) but subsequent to detailed mapping, we extend the fault trace northwards (Fig. 10). In this area, the León Thrust splits northwards into several branches, which is a common feature of other major thrusts of the Cantabrian Zone (compare the León Thrust splitting with the Somiedo and the Sobia Thrusts branching northwards, Fig. 10). This lateral change is evidence of the difficulties in thrust propagation northwards, from a southern sector dominated by major thrusts to a northern sector where shortening is accommodated by folds (Julivert and Arboleya, 1984a, b) or thrust-propagation folds (Alonso et al, 1991; Alonso and Marcos, 1992; Bulnes and Aller, 2002). The westernmost splay of the León Fault cuts and folds the overlying thrust units, named Tameza and Somiedo, by way of a thrust propagation fold (Figs. 9 and 10). Further north, the main splay of the León Fault probably corresponds with the Granda Thrust, which is also a breaching thrust (Alonso and Marcos, 1992) (Fig. 5).

The splitting of the León Thrust is also recorded by displacement changes along its trace. This dis-

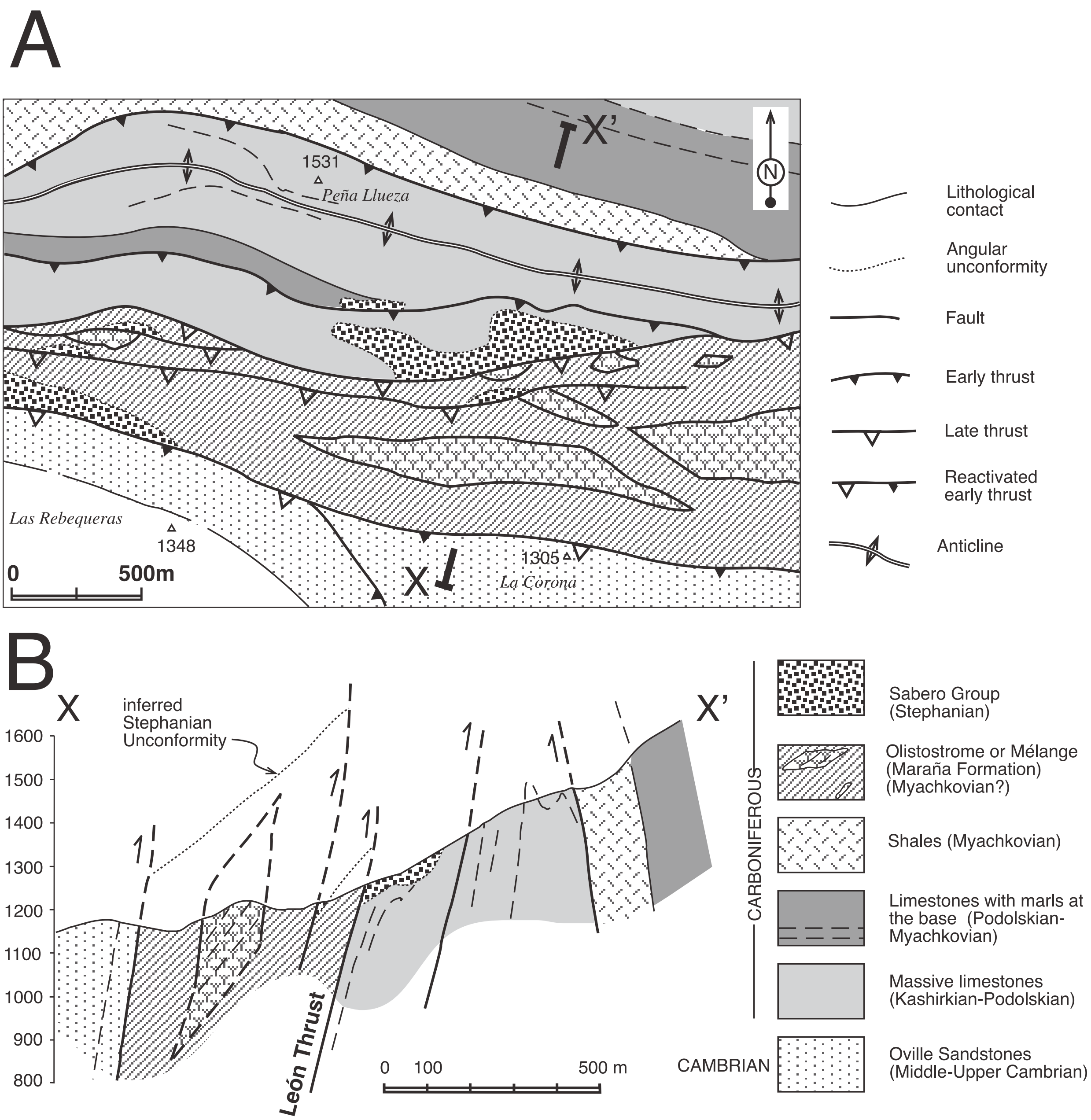

FIGURE 8 | **A) Geological map and B) detailed section across the León Thrust close to the Gold Mine of Salamón. Location in Fig. 4.**

placement is some 20 km in the Porma sector (Fig. 6) and about 9 km for the fault and its splays in the Sobia sector (Fig. 7). This change could imply a strong counterclockwise rotational movement of the hangingwall of the León Thrust, although, in the west, the thrust probably transfers part of its displacement to the Pajares Fault (Aller, 1986), which we have interpreted as an out-of-sequence back-thrust because it also cuts many earlier structures (Figs. 7A and 9).

The León Fault displays all structural features of breaching thrusts, cutting across earlier structures in the footwall whereas in the hanging wall it presents some well-developed flat regions (Figs. 6, 7, 9, and 10). The most common structural relationship between the León Fault and its footwall is the truncation of earlier structures: thrust surfaces (Sobia and Aramo thrusts) and both frontal and lateral folds related to the thrust sheets (Figs. 5 and 9). In some places, the truncation of previous structures causes the León Fault to

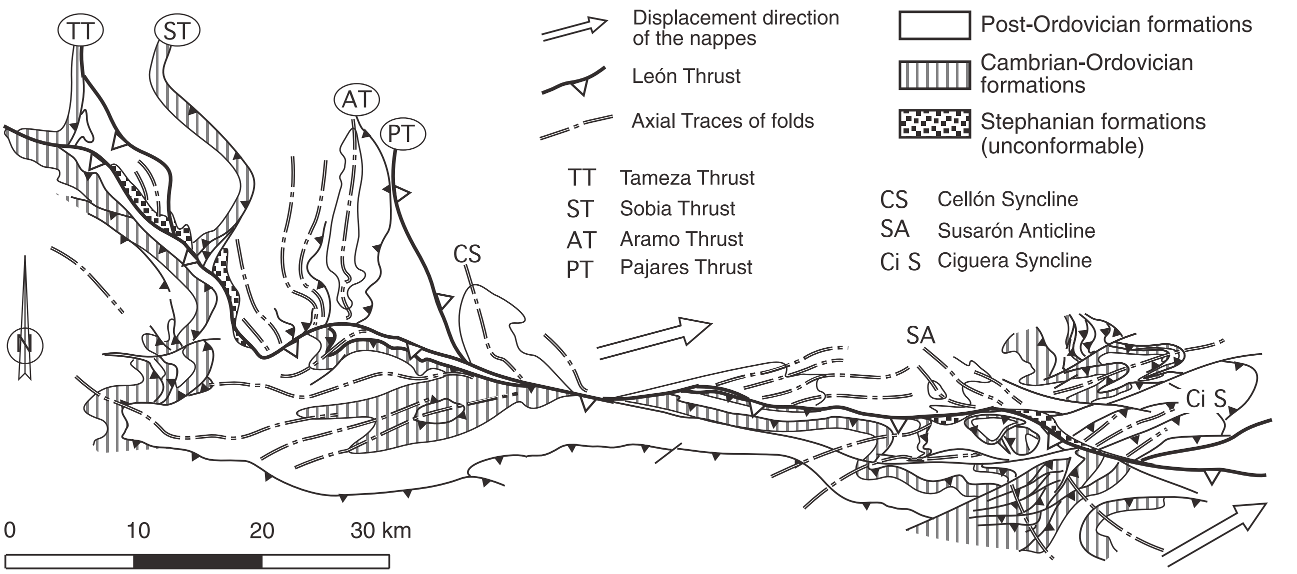

FIGURE 9 | **Structural sketch of the central sector of the León Thrust showing its relation with the surrounding structures.**

carry younger rocks over older ones, as shown in Figs. 6A, 7A, 8, and 10, or viceversa (Figs. 4 and 10).

Duplication of former thrust sheets as a result of the development of the León Thrust and consequential paleogeographic inversion.

When a breaching thrust attains several kms of displacement it can give rise to duplication of the former thrust sheets at regional scale (Fig. 2B). In order to understand this type of duplication caused by the León Fault, the Paleozoic paleogeography in the Cantabrian Zone must first be described. The general stratigraphic succession of the area is shown in Figs. 4 and 11. Whereas the preorogenic succession ranges from Cambrian to Late Devonian and consists of marine sediments derived from the core of the arc, the synorogenic succession is Carboniferous and consists of sediments that were derived from the hinterland in the west (Julivert, 1978). The upper part of the synorogenic sequence has not been illustrated in Fig. 11 because it displays great variations in facies and thickness and several syntectonic unconformities.

The preservation of the preorogenic sequence in the Cantabrian Zone depends on the presence of a low-angle unconformity of Fammenian age which is located at the base of the Ermita Formation, resulting in a wedge which becomes gradually thinner towards the center of the arc (Fig. 12A). Thus, in the western part of the Cantabrian Zone, the pre-Carboniferous Paleozoic succession is almost complete, while in the eastern part, Devonian rocks are not preserved. In fact, in the easternmost part of the Ponga Nappe Province and in Picos de Europa Province, even Ordovician-Silurian rocks are not preserved (Figs. 4, 5, and 12). This paleogeographic pattern is clear in the northern arm of the arc, where thrust displacement is usually small, not exceeding 5 km, both in the former and in the out of sequence thrusts, and therefore the initial paleogeography was not very disturbed during thrusting. However, in the southern branch of the arc, this thinning of the sedimentary wedge towards the center of the arch highlights a duplication when crossing the León Fault, where the sequence of the Forcada Nappe is less complete than that of the Laviana Nappe, located ahead of it (Fig. 12B). Such a pattern implies a paleogeographic inversion similar to that which occurs by erosion of breaching thrusts (Fig. 1). In fact, the thrust sheets located in the hangingwall of the León fault are duplicated in its footwall in the same order. Thus, the stratigraphic succession of the Forcada Nappe is very similar to the Lower Ricacabiello Nappe and the stratigraphic record of the Bodón Nappe is in its turn close to the Laviana Nappe (Fig. 12B). That stratigraphic correlation is not only supported by the erosion level of the Ermita unconformity. For instance, a characteristic condensed succession of Carboniferous age, known as Ricacabiello Formation (Sjerp, 1967) only occurs in the Forcada Nappe and the foremost thrust sheets of the Ponga Nappe Province (Heredia, 1991) (Fig. 12B). Taking the stratigraphic features of the aforementioned nappes into account, the simplest solution would consider the Forcada and Riosol-Lower Ricacabiello Nappes as one tectonic unit and the Bodón, Laviana, Rioseco and Upper Ricacabiello Nappes as a different imbricate system. The later development of the León Fault as a breaching thrust explains their duplication on the map (Figs. 6 and 13). The León Thrust could

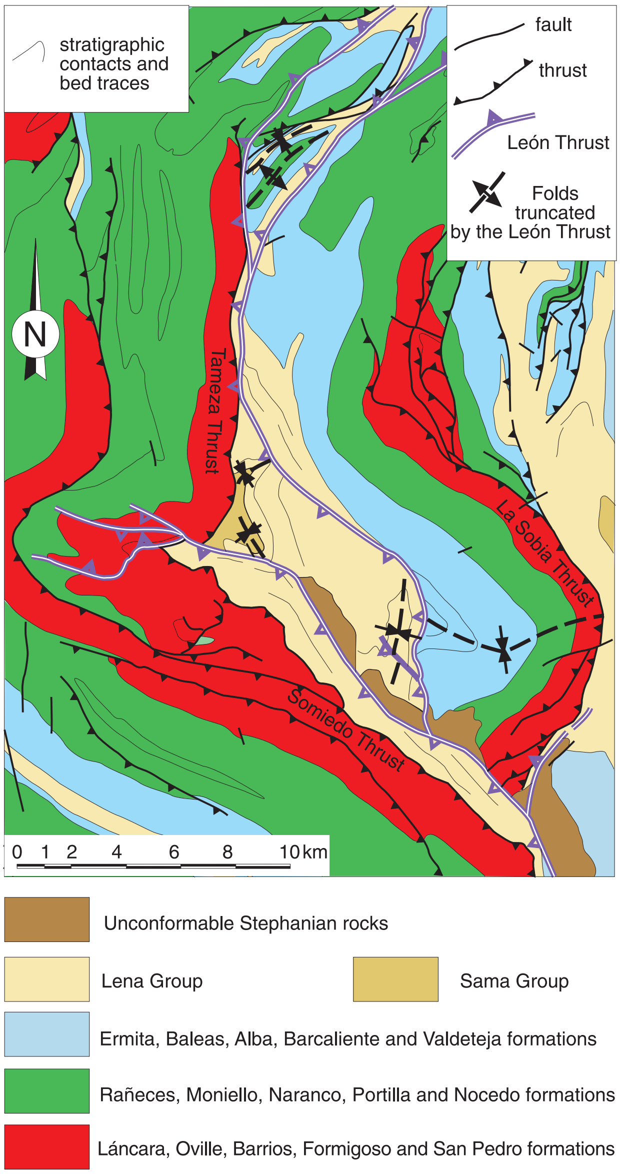

FIGURE 10 | **Geological map of the Teverga area showing the relationship between the León Fault and other regional structures, such as earlier thrusts and folds. The Tameza and Somiedo thrusts are deformed by the León Thrust according to a thrust-propagation fold model. Location in Fig. 4.**

reutilize the foremost part of the Bodón Thrust, however, we cannot determine accurately the primitive location and displacement of the original Bodón Nappe, because its foremost sector is deeply eroded (Fig. 6C and D).

The rocks exposed in the footwall of the Forcada-Riosol Nappe (Pisuerga-Carrión Province) also became duplicated as a result of the development of the León Thrust (Figs. 6E and 13). These rocks occur both at the foremost sector of the Forcada-Riosol Nappe in the Esla valley, and in the Porma valley, in the hanging wall of the León Thrust (Fig. 13). Here, the Pisuerga-Carrión Province was uplifted upon the Central Coal Basin. The Carboniferous succession underlying the Forcada Nappe in the Porma valley has until now been considered as part of the Central Coal Basin (Julivert, 1967; Aller, 1986; Barba, 1991; Heredia, 1991, among others) (Fig. 5), but its olistostromic-mélange facies (Suárez et al., 1996; Alonso et al, 2006) make it equivalent to the Maraña Formation (Heredia, 1991) of the Pisuerga-Carrión Province, rather than to the well-stratified succession of the Central Coal Basin situated in the footwall of the León Thrust in this sector. Therefore, both the Maraña Formation and the mélange of the Porma valley should be assigned to the Pisuerga-Carrión province. The exhumation of the footwall of the Forcada-Riosol Nappe in the hanging wall of the León Thrust indicates that this breaching thrust is rooted at the lowest regional detachment (Figs. 6 and 13).

Duplications of the former thrust units as result of the development of the León Thrust also occur in the southwestern and southeastern sectors of the Cantabrian Zone. In the western sector of the Cantabrian Zone, the León Thrust caused the duplication of the early nappes: the Somiedo Nappe and the Teverga Coal Basin in the hangingwall, correspond to the Sobia Nappe and to the Quirós Coal Basin in the footwall, respectively (Figs. 7C and 13). Fernández González (1990, 1993) has reported the close stratigraphic correspondence between the Teverga and Quirós coal basins, which is consistent with Fig. 7C. Regarding the pre-Carboniferous succession, a paleogeographic inversion occurs in this area which is more subtle than the aforementioned one, because the Sobia Nappe displays a Paleozoic succession more complete than in the easternmost part of the Bodón Nappe (Fig. 14). In this area, the paleogeographic boundaries such as the eastern boundary of the Naranco Formation (Hc in Fig. 14) are perpendicular to the transport direction of the nappes (Alonso et al, 2008). If the Sobia Nappe were the same thrust sheet as the Bodón Nappe, its stratigraphic succession (B in Fig. 14), including 300 m of the Naranco Formation, should have the paleogeographic position B´ in Fig. 14. Therefore, the Sobia Nappe can be interpreted as the foremost area of the Somiedo Nappe, which came apart from it as a result of later development of the León Fault (Figs. 7 and 13).

The most outstanding paleogeographic inversion is observed in the eastern sector of the Cantabrian Zone, where the Fold and Nappe Province displays facies closer to the craton (Brouwer's Astur-Leonese facies, 1964) than in the Pisuerga-Carrión Province (Brouwer's Palentine facies, 1964), and with the boundary between both provinces being the León Fault (Fig. 5). The Palentine Nappes of the Pisuerga-Carrión Province (Fig. 15) comprise Devonian rocks with marine facies deeper than those of the Fold and Nappe Province. This represents a paleogeographic anomaly for which different explanations have been postulated: autochthonist (Kullmann and Schönenberg, 1978) or allochtonist, either with nappes derived from the north (Ambrose, 1972) or with gravitational nappes derived from the south (Frankenfeld, 1983, Keller et al., 2007). The current arrangement of both domains on the geological map can be easily explained with the interpretation of the León Fault as a breaching thrust (Fig. 15). In this model, a paleogeographically more internal domain than the Cantabrian Zone, probably derived from the Westasturian-Leonese Zone, to the south (see Fig. 4A) would have first been emplaced upon the Cantabrian Zone giving rise to the so-called Palentine nappes (Rodríguez Fernández, 1994). Then, a second deeper thrust (León Thrust) rooted in the Cantabrian Zone would have cut across the first one (Fig. 15), although in this sector there are several faults rather than one isolated fault. In this area, Keller et al. (2007) considered the León-Ruesga Fault (Fig. 5) as a south-dipping reverse fault involving the pre-Paleozoic basement. However, its current attitude is north dipping and the top of the basement is probably higher in the northern fault block than in the southern one (Gallastegui, 2000), as depicted in the cross-section in Fig. 6. The present overturned attitude of the León Thrust in this sector (Fig. 15) may be mainly attributed to a late Variscan N-S shortening recorded by unconformable Stephanian rocks. Previous thrust-related folds were tightened and their vergence became southerly during this deformation, with a consequent thrust overturning in the southern arm of the Cantabrian Zone (Alonso, 1987, 1989). South of the Ruesga Fault zone is a domain known as the Valsurbio Dome, which exhibits a well-developed Devonian succession, equivalent to the one in the Somiedo Unit (Fig. 5) (Koopmans, 1962). The Valsurbio Dome, although originating from Variscan deformation, was strongly tightened during the Alpine deformation (Marín et al., 1995) (Fig. 15).

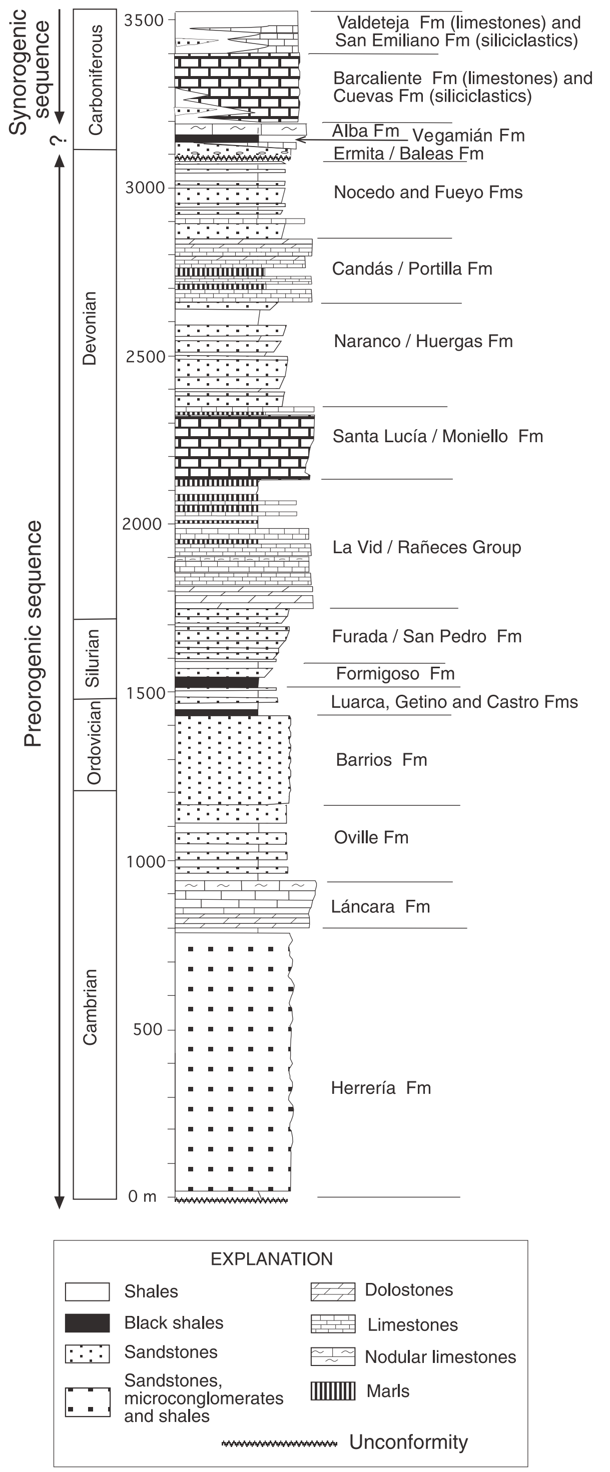

FIGURE 11 | **Generalized stratigraphic column of the preorogenic sequence and the lower part of the synorogenic sequence of the Cantabrian Zone.**

To sum up, the interpretation of the León Fault as a breaching thrust allows a consistent reconstruction of the preorogenic basin (Figs. 6D and 7B), such that the paleogeographic anomalies disappear once the displacement along the León Thrust is removed.

IMPLICATIONS OF THE NEW INTERPRETATION OF THE LEÓN FAULT IN THE GEOLOGICAL SUBDIVISION OF THE CANTABRIAN ZONE

The geological division of the Cantabrian Zone based on the new interpretation of the León Fault is shown in Fig. 16. Unlike the previous division (Fig. 5), the new one considers the Ponga Nappe Province and the Central Coal Basin to be the same unit as the Bodón Unit, since both are characterised by the same thrust sheets and their current separation is the result of the later development of the León Thrust (Figs. 6 and 13). Accordingly, the Bodón Unit and the Ponga Nappe Province represent a single

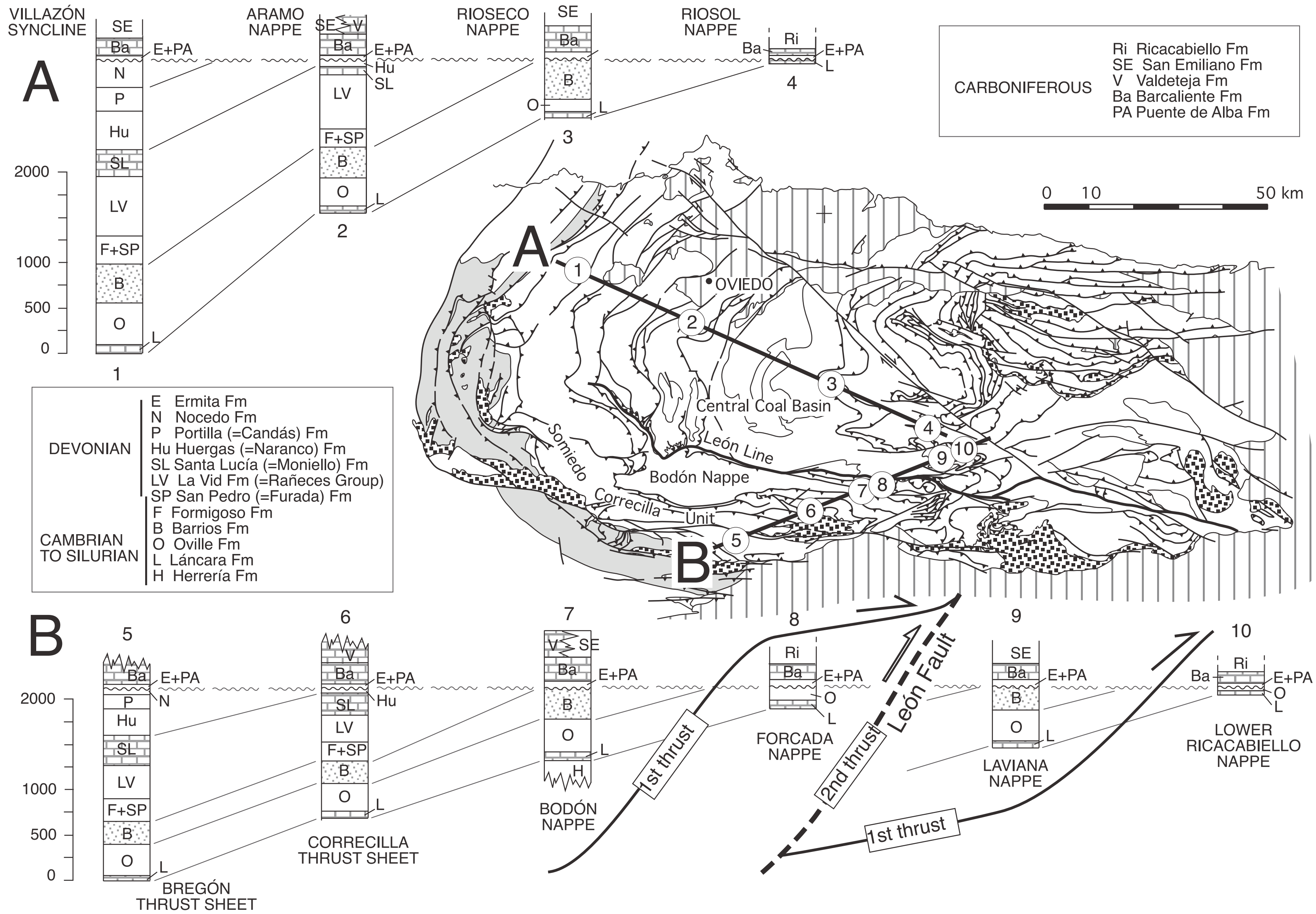

FIGURE 12 **A) Stratigraphic columns in different tectonic units across the northern and B) southern branches of the Cantabrian Zone. Notice the paleogeographic inversion across the León Fault.**

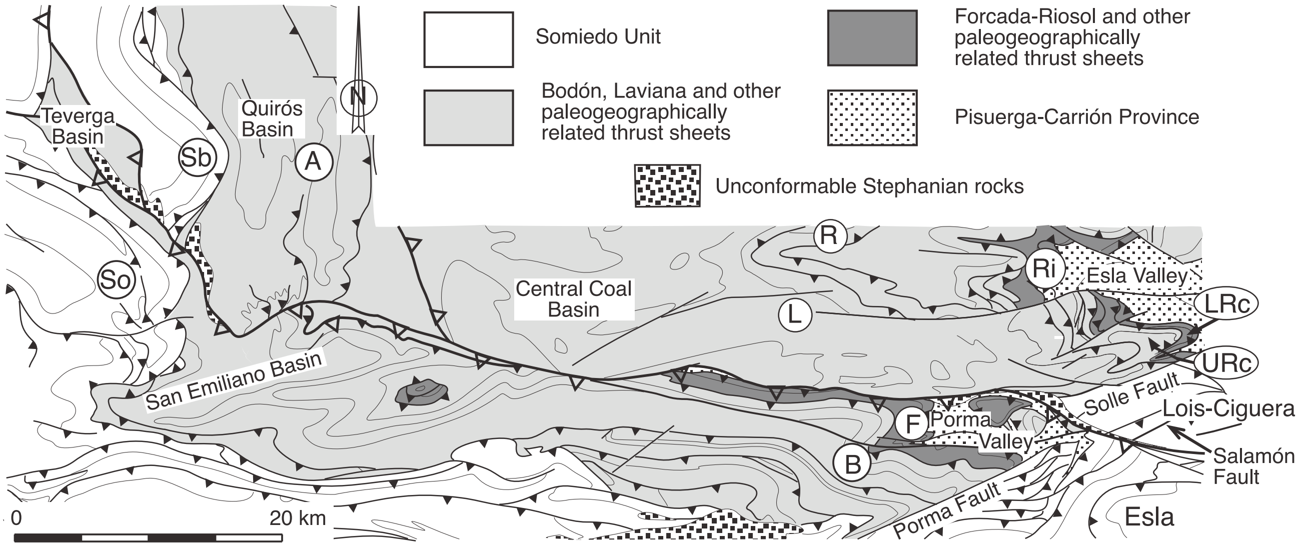

FIGURE 13 | **FIGURE 13 Structural sketch of the central sector of the León Thrust showing the duplications of the thrust units it gives rise to. The same abbreviations for the tectonic units as in Fig. 5.**

thrust sequence, instead of two different and subsequent thrust sequences (Pérez Estaún and Bastida, 1990).

The Sobia Nappe is considered the more advanced part of the Somiedo Nappe and not as part of the Bodón Unit, which was the previous interpretation (Marcos, 1968 a; Julivert, 1971a; Pérez Estaún et al., 1988; among others) (Figs. 7 and 13).

The new division of the Cantabrian Zone is more consistent with the stratigraphic features of the tectonic units than the previous division, because the paleogeographic inversions disappear and a simple paleogeographic pattern is obtained after restoring the León breaching Thrust. Therefore, the "paleogeographic anomalies" of the Cantabrian Zone can be explained through structural restorations. The Picos de Europa Province has been included within the Bodón-Ponga Province (Fig. 16), because its preorogenic succession is paleogeographically equivalent to the more advanced part of the Ponga Region.

The new interpretation of the León Fault implies the modification of previously assumed thrust sequences in the Cantabrian Zone in accordance with the orogenic wedges theory (Davis et al, 1984; Morley, 1988; Nieuwland et al, 2000), in which thrusts propagate not only forward (in sequence) but also out of sequence in order to maintain the orogenic wedge slope during its growth. Furthermore, the tectonic overload related to the León Thrust allows us to understand how the main synorogenic basin (Central Coal Basin) was preserved in a relatively rear location of the orogenic wedge. This new interpretation also requires a revision of previous tectonostratigraphic models of the Cantabrian Zone (Marcos and Pulgar, 1982). For instance, the Teverga Basin and the Quirós Basin were not two subsequent clastic wedges but a unique foreland basin broken after its infilling, which is consistent with their stratigraphic record (Fernández González, 1990).

The relationship between the León Thrust and the Esla Region

Above, a correlation between different structures, all of them truncated by the León Fault and situated on both of its walls (Forcada, Bodón and Somiedo Nappes, for instance), has been set. In addition, the paleogeographic inversion of the Pisuerga-Carrión Province has been reinterpreted. However, nothing has been said about the area between the Pisuerga-Carrión Province and the aforementioned nappes. The Esla Region is situated in this intermediate area, south of the León Thrust, and represents a particular problem because no apparent duplication of the former thrust sheets nor paleogeographic inversion occurs across the León Fault. The structure of this region consists of thrust duplexes (Alonso, 1987), which contrast with the imbricate system found in the west. The Porma Fault, which is parallel to the tectonic transport direction, divides the two regions and has been interpreted as a tear fault (Alonso, 1987) (Figs. 5 and 13). The so-called Lois-Ciguera sector (Fig. 13) is to the north of the Esla Region and the León Fault. This sector has traditionally been considered as part of the Central Coal Basin (Julivert, 1971a; Aller, 1986, Barba et al., 1991) and of Picos de Europa (Julivert, 1971a) (Fig. 5). Heredia (1991) includes it within the Ponga Nappe Province. Nevertheless, the stratigraphic and structural features of this sector differ both from those of the Central Coal Basin and of the Ponga Nappe Province. In fact, the Lois-Ciguera stratigraphic succession contains a much larger proportion of Carboniferous limestones than the neighbouring sector of the Central Coal Basin (Lillo sector of Aller, 1986). Furthermore, it contains a limestone unit of Baskirian age (Yordas Limestone of Alonso Herrero, 1981), a formation that does not occur in this sector of the Central Coal Basin but in other sectors further towards the hinterland, where it is known as Valdeteja Limestone (Wagner et al., 1971). The advanced location of the Valdeteja Limestone in the Lois-Ciguera sector is consistent with the more advanced position of the Devonian paleogeographic boundaries in the Esla Region with regard to the western sectors, to the west of the Porma Fault (Fig. 17). This implies that either the Solle Fault (Sjerp, 1967), which separates the Lois sector from the Ponga Region and the Central Coal Basin, or the Salamón Fault, located within this sector, could be considered as the northern extension of the Porma Fault (Figure 13). Accordingly, the Lois-Ciguera sector could be attributed to the Esla Region. These two regions would now be apart as a result of the truncation of the Esla Thrust System by the later development of the León Thrust, similar to the western nappes (Figs. 13 and 16).

IMPLICATIONS OF THE NEW INTERPRETATION OF THE LEÓN FAULT IN THE STRUCTURAL EVOLUTION OF THE IBERO-ARMORICAN ARC

New constraints on the kinematic models

The new interpretation of the thrust units in the Cantabrian Zone has implications on the kinematic models proposed for the Ibero-Armorican Arc, the largest feature of the Variscan belt in Western Europe (Fig. 3). Many discussions have arisen about the origin of that arc. The transport directions in the core of the arc give the appearance of a converging motion (Fig. 5) and this arrangement has been interpreted in different ways:

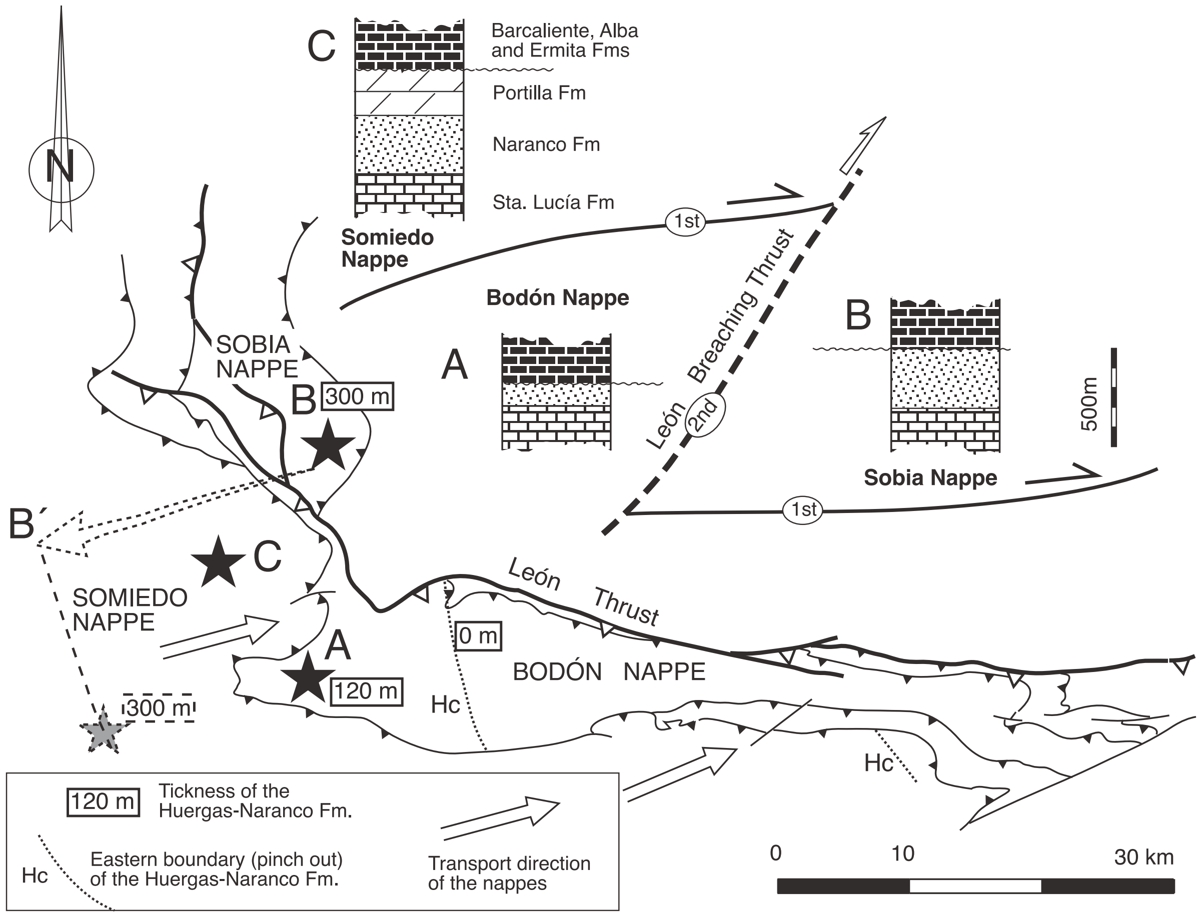

FIGURE 14 | **Stratigraphic columns of the Upper Devonian and Lower Carboniferous in the westernmost sector of A) the Bodón Nappe, B) the Sobia Nappe and C) the Somiedo Nappe. Notice the paleogeographic inversion across the León Fault.**

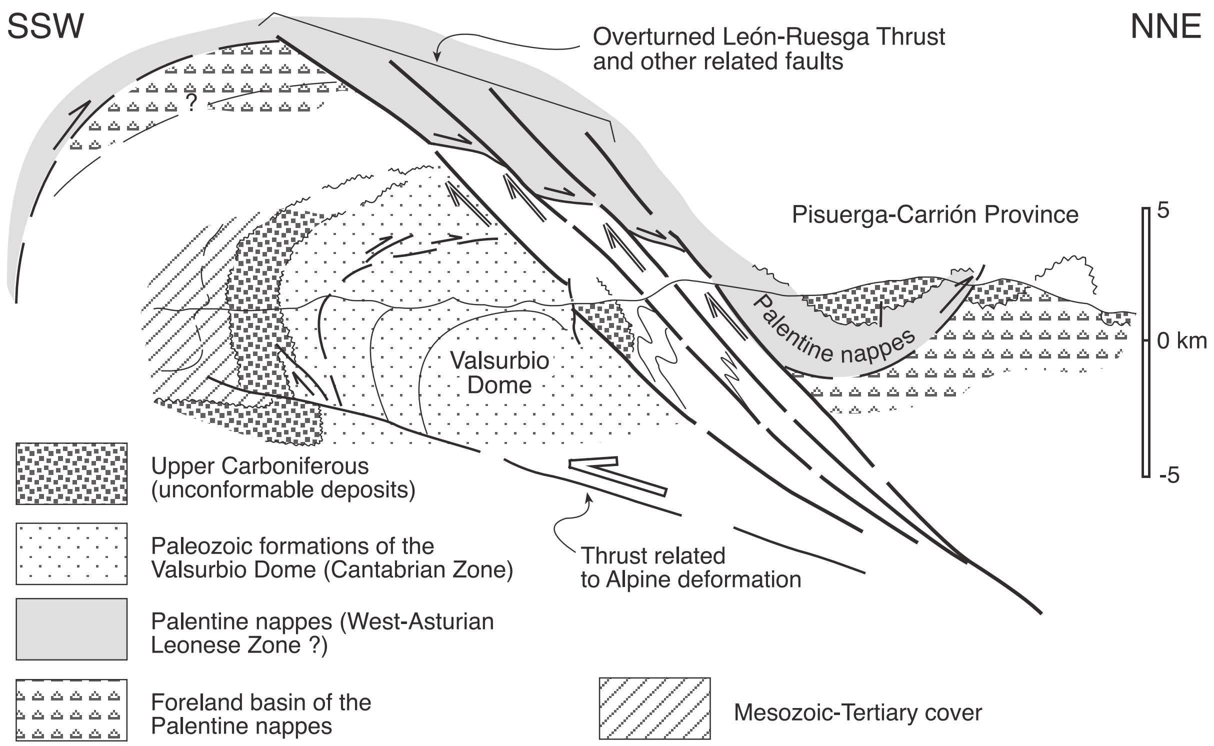

FIGURE 15 **Geological section across the León Thrust with the new interpretation of the relationship between the Pisuerga-Carrión Province and the Valsurbio Dome. Location in Fig. 4**

1. As a result of a rotational emplacement of the nappes, both counterclockwise (Julivert and Arboleya, 1984b) and clockwise (Pérez Estaún et al., 1988), implying a greater shortening in the southern arm of the arc than in the northern one or vice-versa, respectively.

2. Due to a late N-S shortening that bent an initial nearly linear belt (Julivert, 1971b; Julivert and Marcos, 1973; Stewart, 1995; Van der Voo et al., 1997; Weil et al., 2000; Kollmeier et al., 2000; Gutiérrez-Alonso et al., 2004; Weil, 2006),

The new view of some of the thrust units in the Cantabrian Zone favour the second kinematic model, instead of a progressive change in transport direction during nappe emplacement. For instance, rotational models assuming a different transport direction for the Bodón and the Ponga units (Pérez Estaún et al., 1988) should probably be avoided, because both units were the same unit breached later by the León Thrust.

The age of the León Thrust and its role as a persistent anisotropy controlling subsequent deformations

The displacement of the fault as a breaching thrust took place around the Moscovian-Stephanian boundary, because the Forcada-Riosol Nappe overlies a stratigraphic unit containing limestone blocks of Podolskian-Myachkovskian age (Evers, 1967; Heredia, 1991; Suárez et al., 1996) (Fig. 13). The León Thrust, must have moved later than this nappe, because it cuts across them, but before Stephanian times. The present subvertical to overturned attitude of the León Thrust in the southern arm of the Cantabrian Zone (Figs. 6A and 15) may be mainly attributed to a late Variscan N-S shortening, recorded by the unconformable Stephanian sequences. During this deformation, previous thrust-related folds were tightened and their vergence became southerly, with associated thrust overturning in the southern arm of the Asturian Arc (Alonso, 1987, 1989). Minor post-Stephanian reactivations of the León Fault, as shown in Fig. 8, may be attributed to flexural slip associated to this fold tightening. This late episode of N-S shortening has also been documented with paleomagnetic data and was responsible for most of the Asturian Arc curvature (Stewart, 1995; Weil et al., 2000; Weil, 2006).

The large out of sequence León Thrust, which breached and carried for more than 10 km a nappe pile of several kilometres thick, was a major crustal anisotropy, controlling subsequent deformations. For instance, the duplication of the pre-Variscan basement in Fig. 6A, which has been attributed to the Alpine Orogeny (Gallastegui et al., 1997), occurred just to the north of the León fault. We should not rule out that this basement

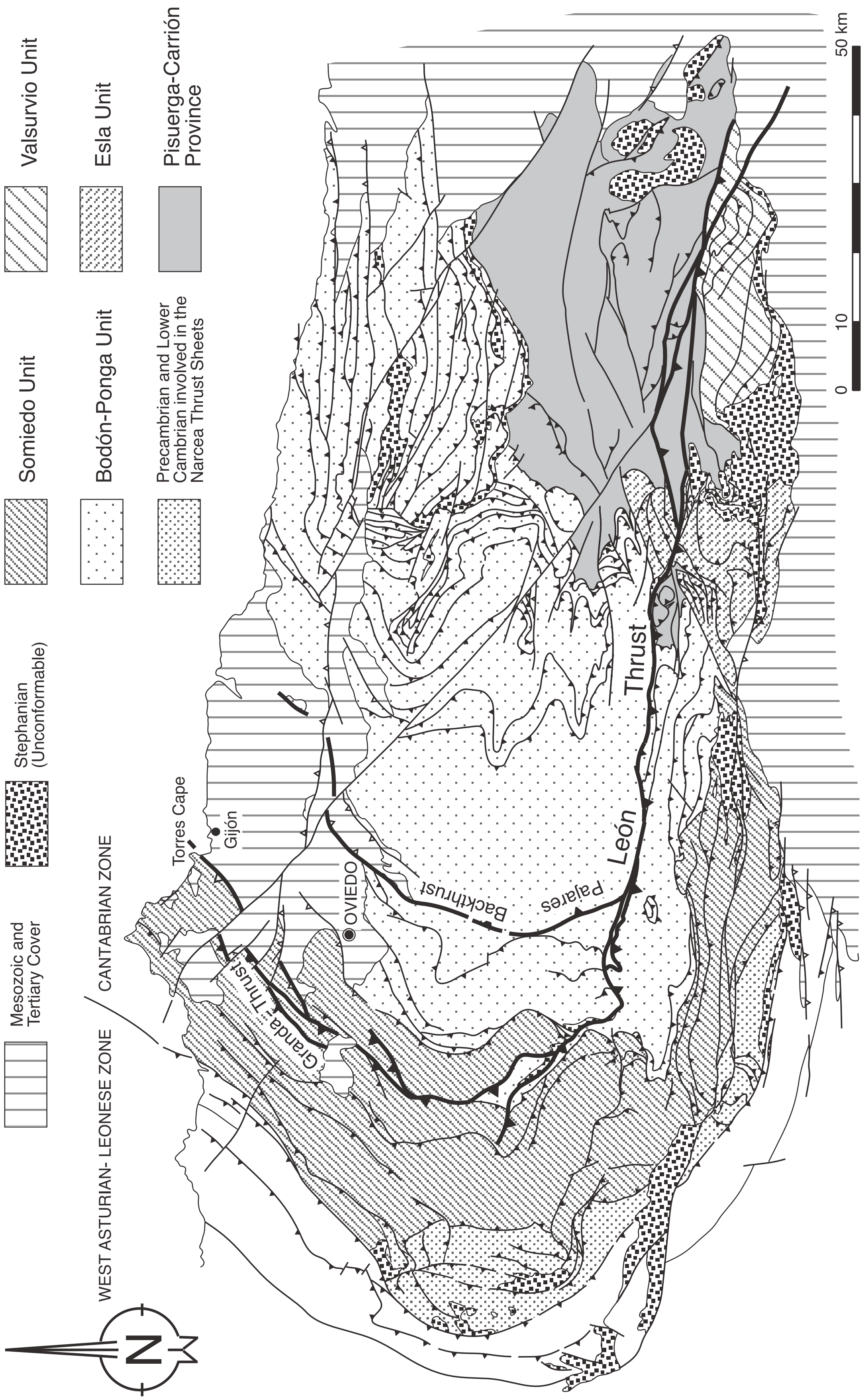

FIGURE 16 | **New division of the Cantabrian Zone into geological domains.**

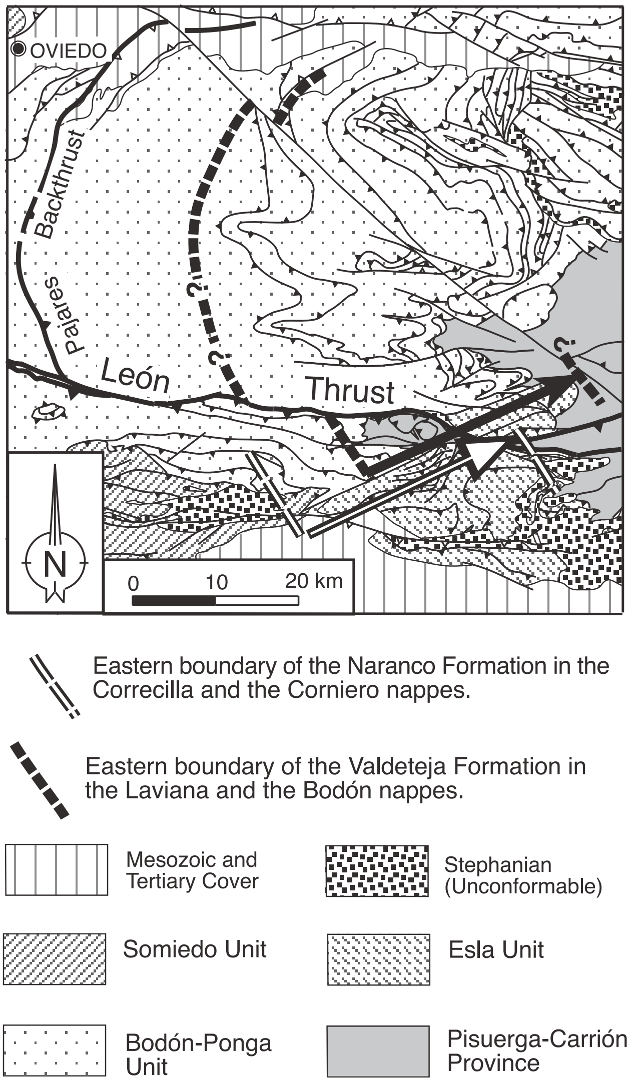

FIGURE 17 | **Eastern boundaries of de Valdeteja and Naranco formations and their strike separation along the Porma and Solle Faults.**

duplication may represent the reactivation of a late-Variscan fault, that contributed to the lower crustal thickening and subsequent lithospheric delamination postulated during the arc tightening (Gutiérrez Alonso et al, 2004). This is consistent with the Early Permian hydrothermal activity and intrusion of small igneous bodies around the León Fault documented by Valverde-Vaquero et al. (1999), Crespo et al. (2000) and Gasparrini et al. (2006). During Alpine orogenesis, the above-mentioned duplication gave rise to the uplift of the northern fault block, as recorded by the present relief, with a regional level of summits higher than in the southern block (Alonso et al., 2007). This uplift is also recorded by the exhumation of late Variscan metamorphism in the northern fault block (Aller and Brime, 1985; García López et al, 2007). The eastern part of the León Fault, named the Ubierna Fault (Fig. 5), was reactivated as a Lower Cretaceous extensional fault and as a reverse fault during the Alpine inversion (Espina et al., 1996). In the western part of the León Fault, a splay reverse fault overriding Cretaceous sediments also records the Alpine uplift of the northern fault block (Alonso et al., 2007).

COMPARISONS OF THE PALEOGEOGRAPHIC INVERSION CAUSED BY THE LEÓN THRUST WITH OTHER OROGEN-SCALE PALEOGEOGRAPHIC INVERSIONS

Well-know examples of paleogeographic inversion occur in the Prealps-Helvétic Nappes (now in reverse order with respect to their initial arrangement) and in the Apennines, where the Ligurian Nappe overtook the Tuscan Nappes (Fig. 18A and B). In both examples, the paleogeographic inversions are related to major klippes or tectonic windows developed mainly as a result of nappe stacking, although small out of sequence displacements truncated the Ligurian Thrust (Fig. 18B). Paleogeographic inversions related to large breaching thrusts may also produce apparent paleogeographic inversions at a regional scale, but these are more difficult to recognize than those related to classical tectonic windows, because both the first thrust and later breaching thrusts usually dip in the same direction, and therefore, the exhumation of a lower tectonic unit in the midst of a upper imbricate thrust system is not evident at first sight (Figs. 4, 6, 7, 13, 18C and D, and compare Fig. $1C_1$ and C_2). In fact, out of sequence breaching thrusts give rise to particular types of tectonic windows where both the rear and leading thrusts are not the same folded thrust as in classical tectonic windows, but subsequent thrusts.

CONCLUSIONS

Out of sequence breaching thrusts are known to be responsible for internal deformation of orogenic wedges in order to maintain their critical taper (Morley, 1988), but no stress has ever been put on the role of this type of thrusts in disrupting the palaeogeographical pattern of the preorogenic sedimentary basins. Large breaching thrusts may duplicate former thrust units in map view and give rise to apparent paleogeographic inversions in a similar way that large tectonic windows do. In fact, out of sequence breaching thrusts give rise to a particular type of tectonic window not evident at first sight because both the rear and leading thrusts bounding the window dip to the same direction. For large breaching thrust displacements, structural correlation between previous truncated structures, located in different fault walls, may be difficult to recognize, resulting in the misinterpretation of a complex

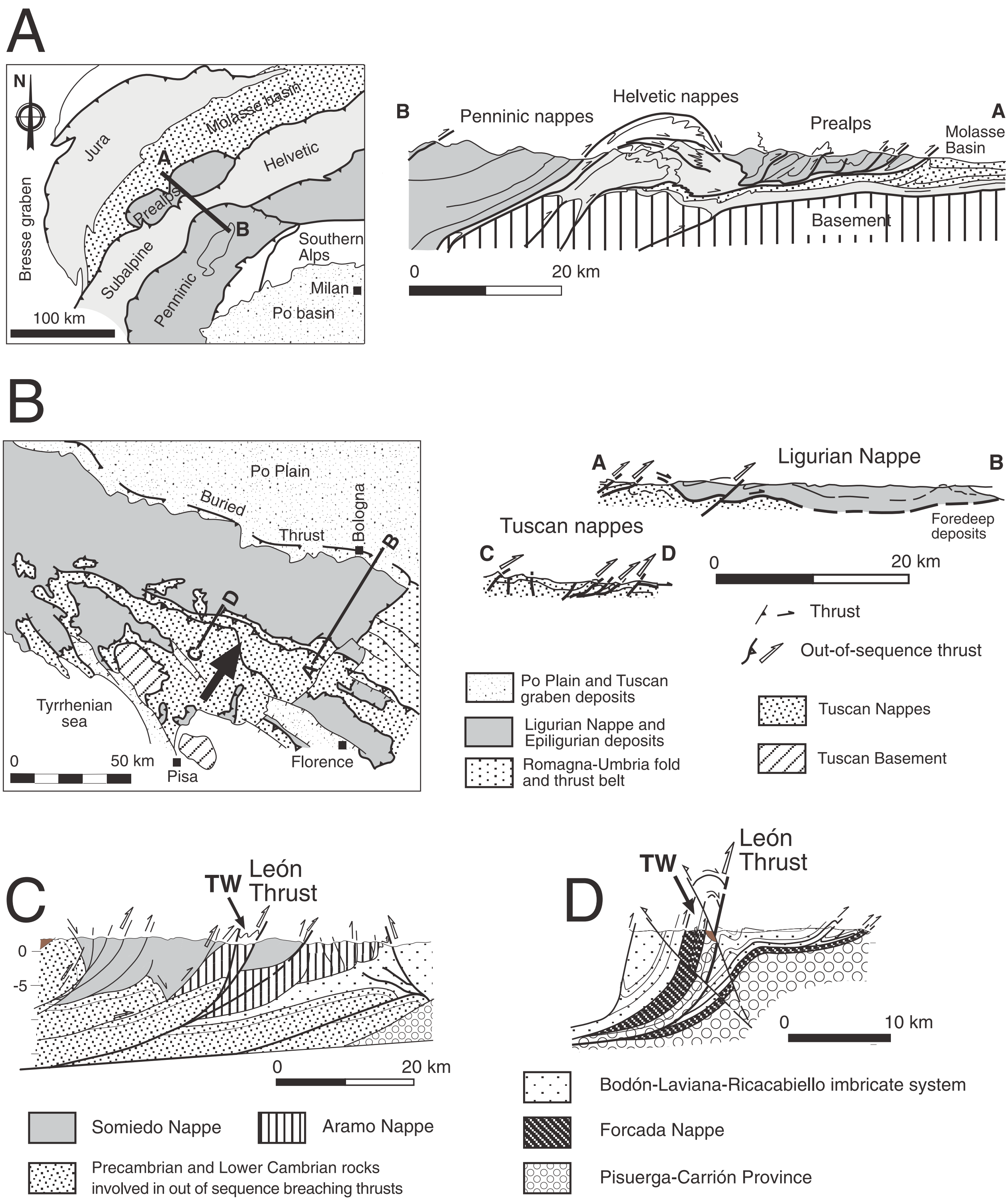

FIGURE 18 **Structural sketches and geological sections across A) the Alps (adapted from Escher et al. 1988) and B) Northern Apennines (adapted from Pini, 1999 and Pini et al, 2004). C) and D) Geological sections across the Somiedo and Porma areas respectively, in the Cantabrian zone. TW: tectonic windows related to the León Thrust.**

palaeogeographical pattern as a primitive feature of the preorogenic sedimentary basin.

The León Fault, an orogen-scale fault located in the Variscan foreland fold-thrust belt of the Iberian Peninsula, has caused much controversy in the understanding of Iberian Paleozoic tectonics, being interpreted either as a primitive synsedimentary fault or a strike-slip fault. The León Fault displays all features of a breaching thrust: it duplicates former thrust sheets and consequently it carried younger rocks over older ones and vice versa. Although locally it cuts across some major earlier thrust surfaces, this fault follows the trace of the Asturian Arc with a trend and attitude similar to that of other thrusts of the Cantabrian Zone with which it shares many other structural features (flats, lateral and frontal ramps, fault-related folds, splitting to the northern branch of the arc). To sum up, the new interpretation presents a simple explanation for the apparently complex structural relationship between the hangingwall and the footwall of the León Fault.

Interpreting the León Fault as a breaching thrust provides a new view of the structure and palaeogeography of the Cantabrian Zone. Several major tectonic units of the Cantabrian Zone, long accepted in the geological literature, must be modified as a result of the new interpretation, because the earlier thrusts are duplicated on the geological map due to the later development of the León Thrust. Hence, the Sobia Nappe is now considered the most advanced part of the Somiedo Nappe while the Forcada and Riosol nappes form one single nappe, whereas the Sobia-Bodón Unit disappears. This implies a new subdivision of the geological domains of the Cantabrian Zone, consistent with the new tectonic units. In this new division, a substantial part of the Fold and Nappe Province is considered to be the same unit as the Ponga Province. Furthermore, the southeast end of the latter (Lois Sector) could be part of the Esla Region.

The new tectonic units here proposed for the Cantabrian Zone also imply a substantial modification of the accepted emplacement sequence of the thrusts. Thus, the Bodón Unit and the Ponga Nappe Province are claimed here to represent one single thrust system, instead of two different and subsequent thrust sequences, as suggested previously. It also has implications on the kinematic models proposed for the Ibero-Armorican Arc, ruling out rotational models assuming a different transport direction for the Bodón and the Ponga units, because both units were the same, breached later by the León Thrust.

Moreover, the explanation of the León Fault as a breaching thrust clarifies the paleogeographic interpretation of the Cantabrian Zone. Some previous interpretations considered that fault as a primitive feature controlling Palaeozoic sedimentation and Variscan deformation. Our new interpretation allows a palinspastic restoration where the pre- and synorogenic basins can be consistently reconstructed, such that the apparent paleogeographic inversions found on the maps of the Cantabrian Zone can be related to the duplication of the former tectonic units.

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