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Sequences of thrusts and displacement transfer in the superposed duplexes of the Esla Nappe Region (Cantabrian Zone, NW Spain)

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Abstract—In a cross-section through the southern arm of the Cantabrian Zone, several duplexes have been identified below the Esla Nappe, which is the uppermost and main thrust sheet of the area. The folds deforming the Esla Nappe are culmination walls linked to frontal and lateral ramps belonging to the lower thrust sheets. The thrust sequence can be established on the basis of quantitative analysis of displacement transfer and out of sequence thrusting. The primitive footwall ramps of the Esla Nappe Region were often subsequently broken by décollements developed in successively lower stratigraphic levels of these footwalls. The kinematics of the lowest duplex are more complicated than those of typical duplexes described elsewhere: some thrusts transfer only part of their displacement to the roof thrust, while the remaining part is accommodated along the higher thrusts of previously emplaced duplexes, cutting out of sequence one or more floor or roof thrusts. Cumulative displacement of the thrusts in this region is about 90 km, giving a present thickness 3 times that of the original pre-orogenic sequence, together with a translation of at least 60 km, for the synorogenic basin.

INTRODUCTION

THE Cantabrian Zone is the unmetamorphosed part of the Hercynian Belt in NW Spain (Lotze 1945, Julivert *et al.* 1972) and forms the core of its arcuate shape. The most outstanding features of the zone are décollement nappes directed towards the centre of the arc and two sets of cross folds (Comte 1959, De Sitter 1959, 1960, Julivert 1971, Julivert & Marcos 1973, Julivert & Arboleya 1984). A genetic relationship between folds and thrusts of the Esla Nappe Region may be postulated, as has been shown by Bastida *et al.* (1984) in the Somiedo Nappe Region. However, in the Cantabrian Zone the relationships between thrusts and folds are more complicated than in linear orogenic belts (e.g. Rocky, Appalachian, Caledonian Mountains) owing to the convergence of several nappes towards the centre of the arc. Folds and faults related to the earlier thrusts have undergone subsequent shortening in other directions as a consequence of the convergent emplacement of later thrusts.

The Esla Nappe Region is located at the southern boundary of the Cantabrian Zone (Fig. 1). Almost the entire Paleozoic era is represented in the stratigraphic sequence of this region (Comte 1959, De Sitter 1959). Sedimentation took place on a stable marine platform producing 3–5 km of Cambrian–Namurian strata, which thin towards the NE as a result of a low-angle unconformity situated in the Upper Devonian. From Namurian B to Stephanian, a succession of up to 5 km of synorogenic sediments display great variations in facies and thickness with many unconformities. Some of these are localized as a result of synsedimentary tectonic activity (Alonso 1982a & b, 1985).

The Esla Nappe, the main thrust sheet of the studied area, was initially studied by De Sitter (1959) and Rupke (1965) who proposed that the thrust cut up-section towards the NE in the direction of inferred transport. Arboleya (1978) inferred the same direction of displacement, based on the orientation of cleavage and boudins located in a narrow fault zone at the base of the nappe, together with folds associated with the frontal hangingwall ramp (Julivert & Arboleya 1984).

Thrust sheet emplacement in the Esla Nappe Region occurred in the Moscovian stage (Upper Carboniferous), as inferred from the syntectonic unconformities covering the thrusts and the presence of olistoliths derived from the toe denudation. However, deformation continued, probably as a result of the emplacement of later nappes of the Cantabrian Zone outside this region and whose direction of advance is convergent with respect to the Esla thrust sheets. The variation in shortening direction throughout the orogenic period makes it difficult to locate plane-strain sections. Tear faults related to the Esla thrusts were later reactivated as reverse faults producing an outcrop pattern in which lower and rear sectors of the thrust sheets outcrop together with upper and more advanced ones. This disposition allows a relatively complete analysis of the displacement transfers between the various faults.

This paper presents the geometry of the thrust systems of the Esla Region, discusses their thrusting and folding relationships, and then presents a quantitative displacement analysis of the different thrusts by means of a balanced sequence diagram.

THE STRUCTURE OF THE ESLA NAPPE REGION

Figure 2 shows the geology of the Esla Nappe Region, Fig. 3 the names of the principal structures (thrust sheets, thrust systems and main folds of the area) and Fig. 4(a) is a cross-section containing the direction of advance of the thrust sheets.

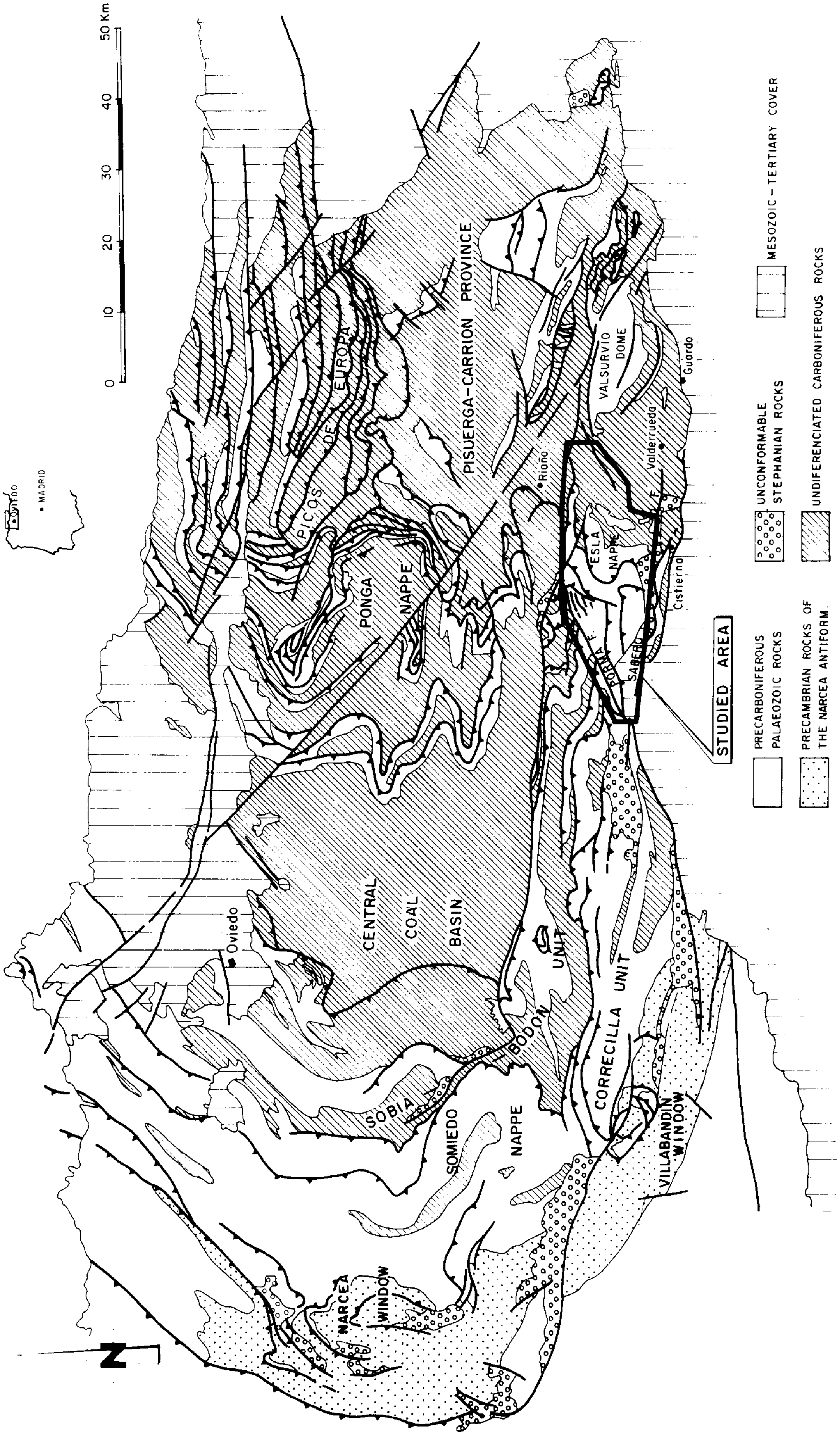


Fig. 1. Location of the studied area within the Cantabrian Zone.

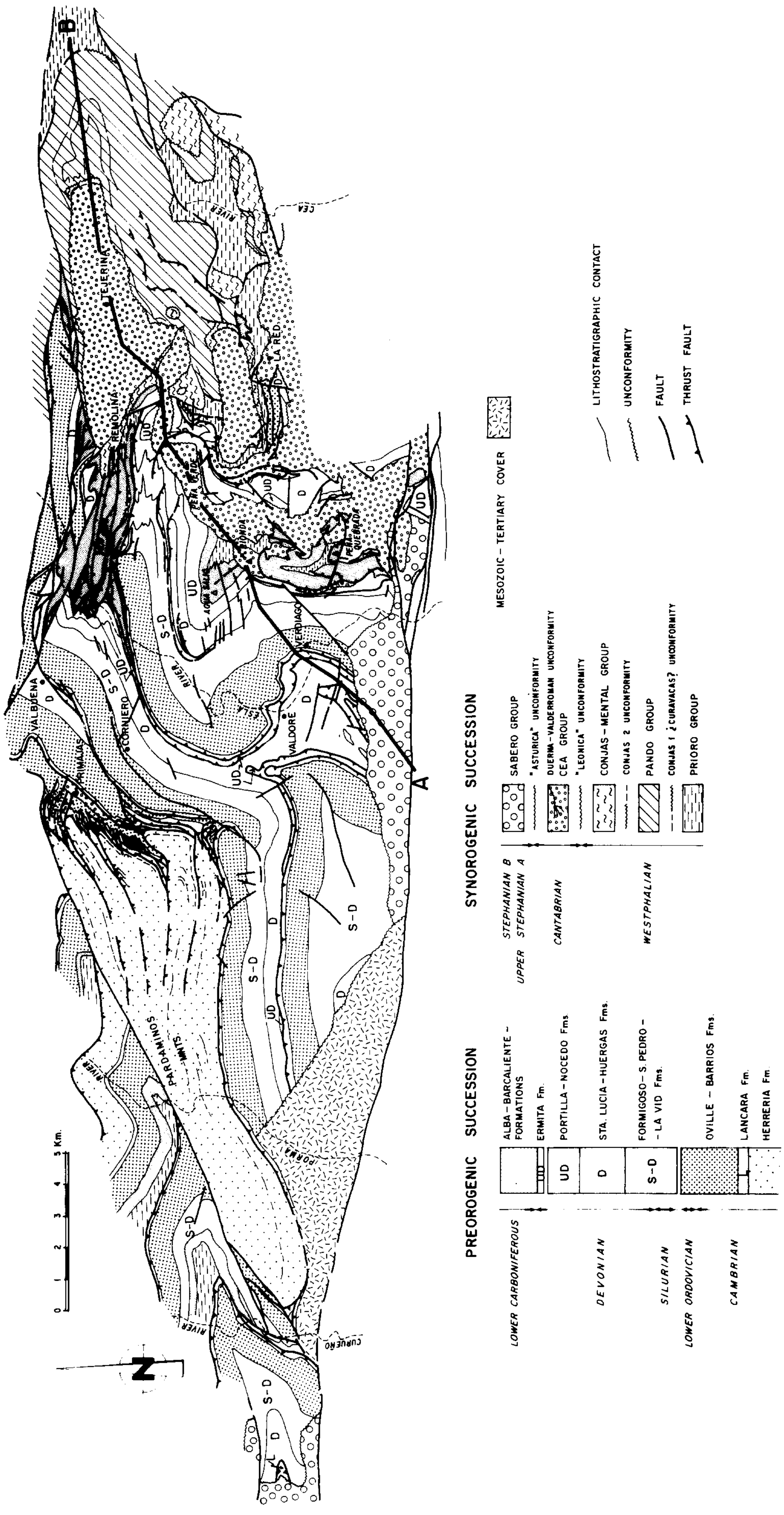


Fig. 2. Simplified geological map of the Esla Nappe Region. A–B: trace of the geological section of Fig. 4.

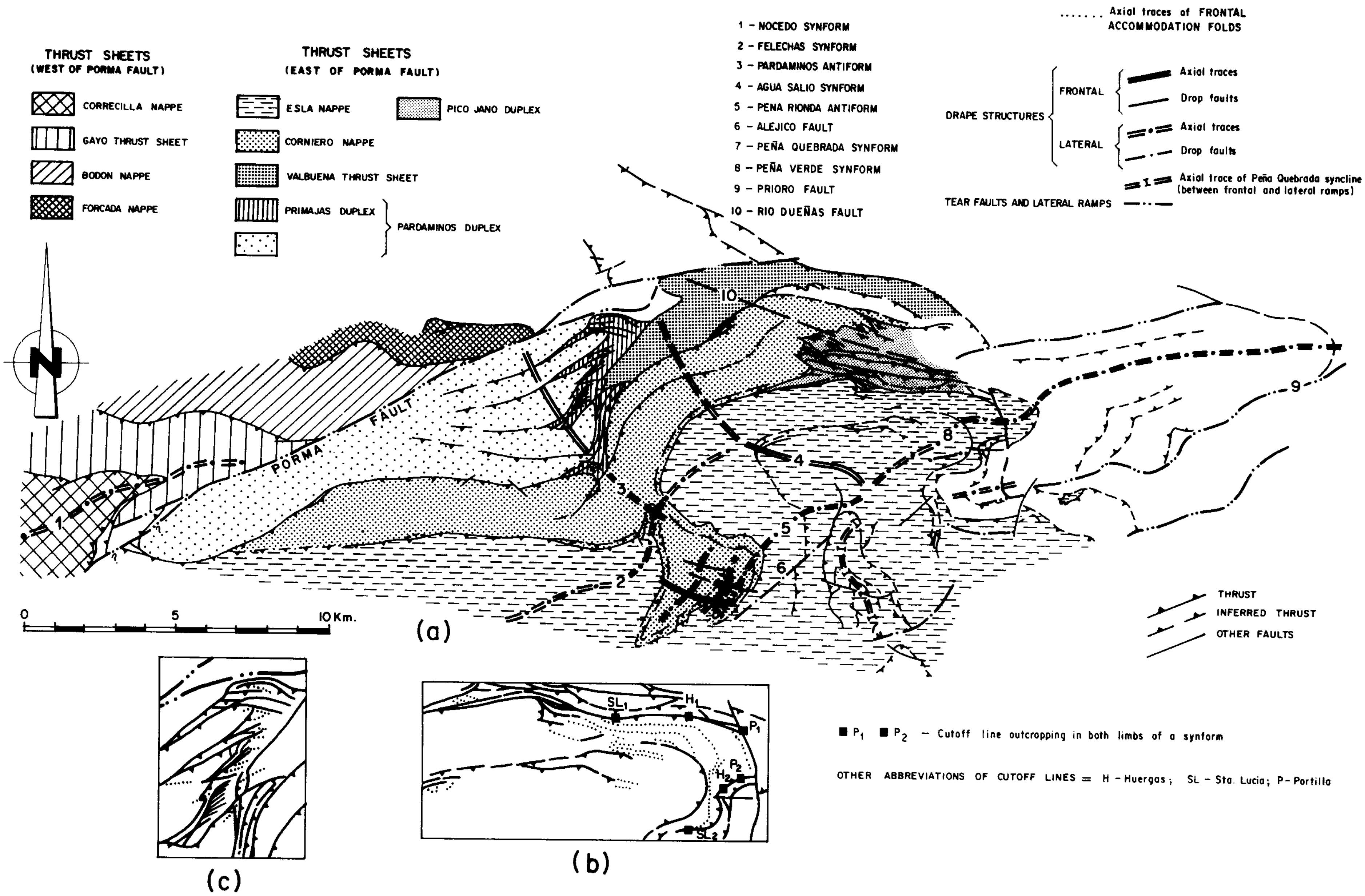


Fig. 3. (a) Names of main folds, thrust sheets and thrust systems of the Esla Nappe Region. The outcrop pattern of the thrust in the northernmost part of the map has been restored to an estimated position prior to the movement of the Rio Dueñas strike-slip fault system. (b) and (c) Frontal accommodation folds in the Esla Nappe and Primajas and Pardaminos duplexes.

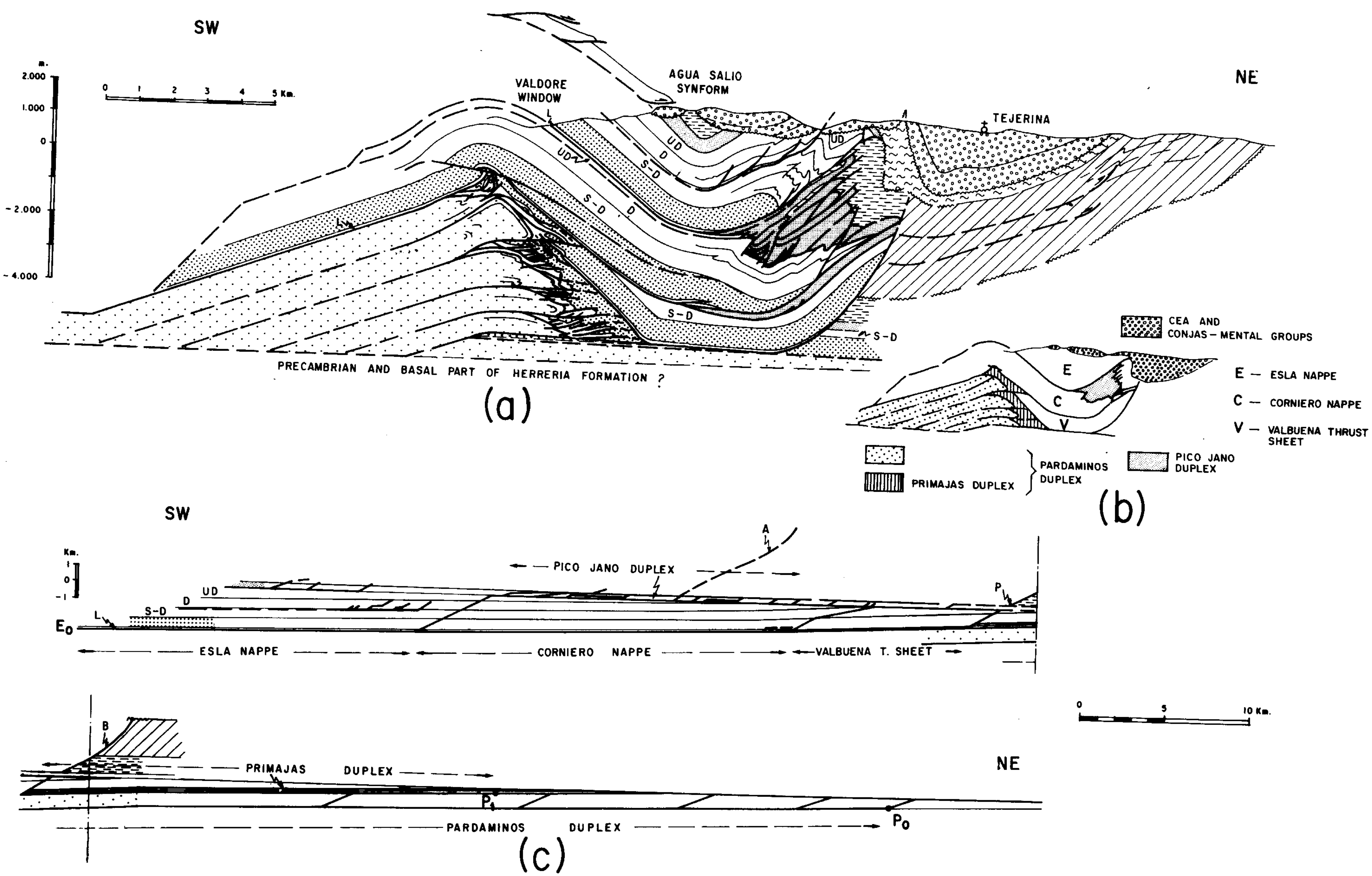


Fig. 4. (a) Geological section along lateral folds of the nappes in the Esla Nappe Region. Location and legend as in Fig. 2. (b) Names of main thrust sheets and thrust systems in simplified section (a). (c) Palinspastic restoration of section (a). A and B are possible extreme locations of upper part of Valbuena Thrust, assuming that the cumulative displacement of Pico Jano Duplex, basal thrust of Portilla Formation and Corniero Thrust is untransferred (A) or wholly transferred (B) forward of P point along the top of Barcaliente Formation.

Thrusts and other faults

The Esla Nappe is the highest thrust sheet and displays a Cambrian–Namurian succession. Underlying this nappe at its front is the Pico Jano Duplex, which is an antiformal stack consisting of Lower Carboniferous rocks (Fig. 4). Underneath this lies the Corniero Nappe and the Valbuena Thrust Sheet, made up of a succession from Cambrian to Upper Devonian rocks. The lower part of the structure is composed of the Primajas and Pardaminos duplexes, comprising exclusively Cambrian rocks. The Primajas Duplex is a typical duplex with horses made up from the Lancara Formation and the basal part of the Oville Formation (Lower–Middle Cambrian), whilst the Pardaminos Duplex consists of a great antiformal stack with each horse composed of Herrería Formation (Lower Cambrian) together with some horses of the Primajas Duplex (Fig. 4). One of the Pardaminos thrusts divides the Primajas Duplex into two parts, and roofs into the Corniero Thrust (Fig. 4a).

Figure 3 shows several structural elements (faults, folds and cut-off lines) that form two structural systems which may be considered as frontal and lateral structures of the thrust sheets. The deformation of these structural elements can be related to the emplacement of lower thrust sheets in the Esla Nappe Region, or to later convergent thrust sheets of the Cantabrian Zone, as explained later.

The major faults (Porma Fault and Prioro Fault) are parallel to the direction of transport and act as tears with respect to certain of the thrust sheets. No structural correlation is possible betyween the two sides of these faults. Thus, the Pardaminos Duplex does not exist to the west of the Porma Fault, while the Bodon and Forcada thrust sheets do not exist to the east (Figs. 2 and 3).

Folds related to lower thrust sheet geometry

The relationship between major folds, transverse to the transport direction of the thrust sheets, can be clearly appreciated from a geological section (Fig. 4a) along the axial surfaces of folds whose limbs may be considered as lateral culmination walls (Butler 1982) related to the thrust sheets. These are called *drape folds* in Fig. 3.

Figure 4(a) shows that the antiformal structure of the Corniero and Esla Nappes, which gives rise to the Valdoré Window, appears above the Pardaminos Duplex. The thrust slices display progressively more open folds towards the lower part of the duplex. Thus folding is a direct geometrical consequence of the successive emplacement of lower thrust sheets. It may also be observed in Fig. 4(a) that the Agua Salio Synform is situated between the Pardaminos frontal culmination wall and the frontal footwall ramp of the Valbuena Thrust.

The axial trace orientations of other folds are parallel to that of the direction of thrust sheet advance. This is the case, for example, with the Peña Rionda Antiform, which determines the southeast boundary of the Valdoré Window. This antiform and the southeast end of the axial trace of the Agua Salio Synform are aligned, a feature which may be attributed to the existence of lateral hangingwall ramps in the Pardaminos Thrust Sheets producing a lateral culmination wall (Fig. 5). The Alejico Fault (Figs. 3 and 5), located over this culmination wall, may be interpreted as a drop fault (Butler 1982). The Peña Quebrada Syncline may indicate the bending of the Corniero and Valbuena thrust sheets between this culmination wall and a frontal footwall ramp (Fig. 3). The development of this syncline between a frontal and lateral structure would explain its anomal-

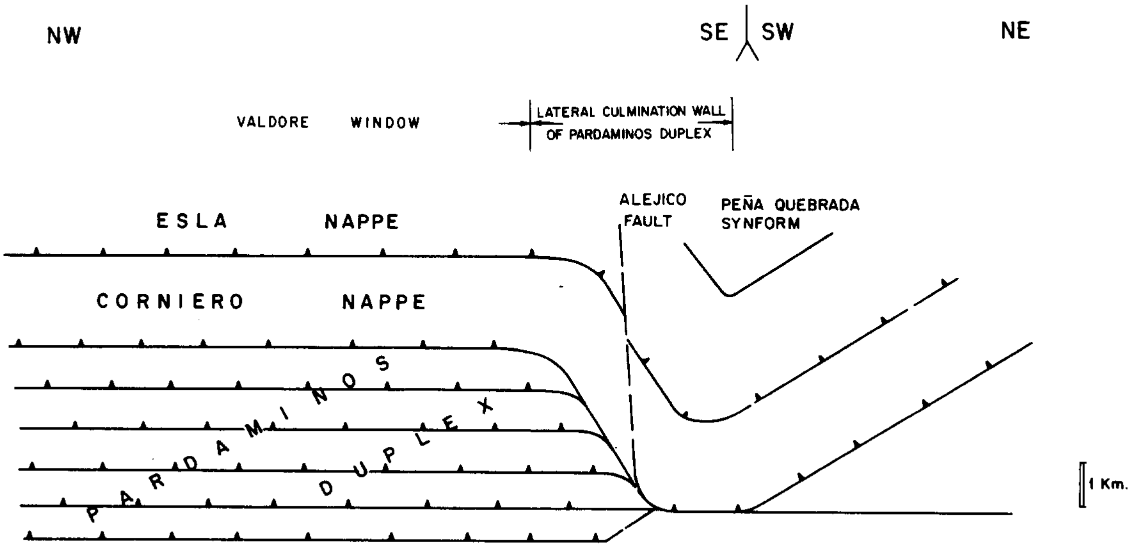


Fig. 5. Geological section with two parts, the left one normal to the transport direction of the nappes and the right one across Peña Quebrada Synform.

ous orientation (N–S) with regard to the other folds in the region.

The other major fold in the region (Peña Verde Syncline) may be explained by the effect of lateral ramps.

Accommodation of thrust displacements by frontal folds

Apart from the folds related to lower thrust sheet geometry, as described above, there are other folds in the Esla Nappe Region, generally of lesser size, which partially or totally accommodate thrust translation, and which have thus been grouped together under the name of *frontal accommodation folds* (Fig. 3b & c). Sometimes these are folds connected with blind thrusts of the kind described by Dahlstrom (1969), Thompson (1981) and Williams & Chapman (1983), or detached folds over the surface of the thrusts which may or may not be blind thrusts. In other cases they are folds situated on frontal hangingwall ramps, the origin of which may be attributed to simple shear affecting the thrust sheet as a whole, according to the mechanism set forth by Ramberg (1959) and applied by Ramsay *et al.* (1983) to folds in the Helvetic nappes. In the Esla Nappe Region good examples of the latter type of folds are located on the Esla Nappe hangingwall ramp (Fig. 4a). The hinges of these folds are deformed by the Peña Verde Syncline (Arboleya 1978) and they show the same disposition as the cut-off lines, both folded by this syncline (Fig. 3b), on the supposition that cut-off lines and folds are frontal structures of the thrust sheets. It is worth emphasising that different structures (frontal folds, cut-off lines, tears) are consistent with the same direction of advance for all the Esla thrust sheets, and that this direction coincides with that obtained by Arboleya (1981) from boudins and cleavages present in the base of the Esla Nappe.

DEFORMATIONS SUBSEQUENT TO THE EMPLACEMENT OF THE THRUST SHEETS OF THE ESLA REGION

Figure 6 shows the present attitude of the structures described above. Deformations subsequent to the Esla Nappe emplacement consist mainly of reverse reactivation of the Porma Fault and final N–S shortening.

A reverse movement of the Porma Fault is necessary to explain the rotation of the frontal geometrical elements of the thrust sheets in a tract to the east of this fault. Such rotation would also explain the partial unfolding of the primitive Agua Salio Synform in its NW sector. It might also have been responsible for the development of Felechas Syncline (Figs. 3 and 7),

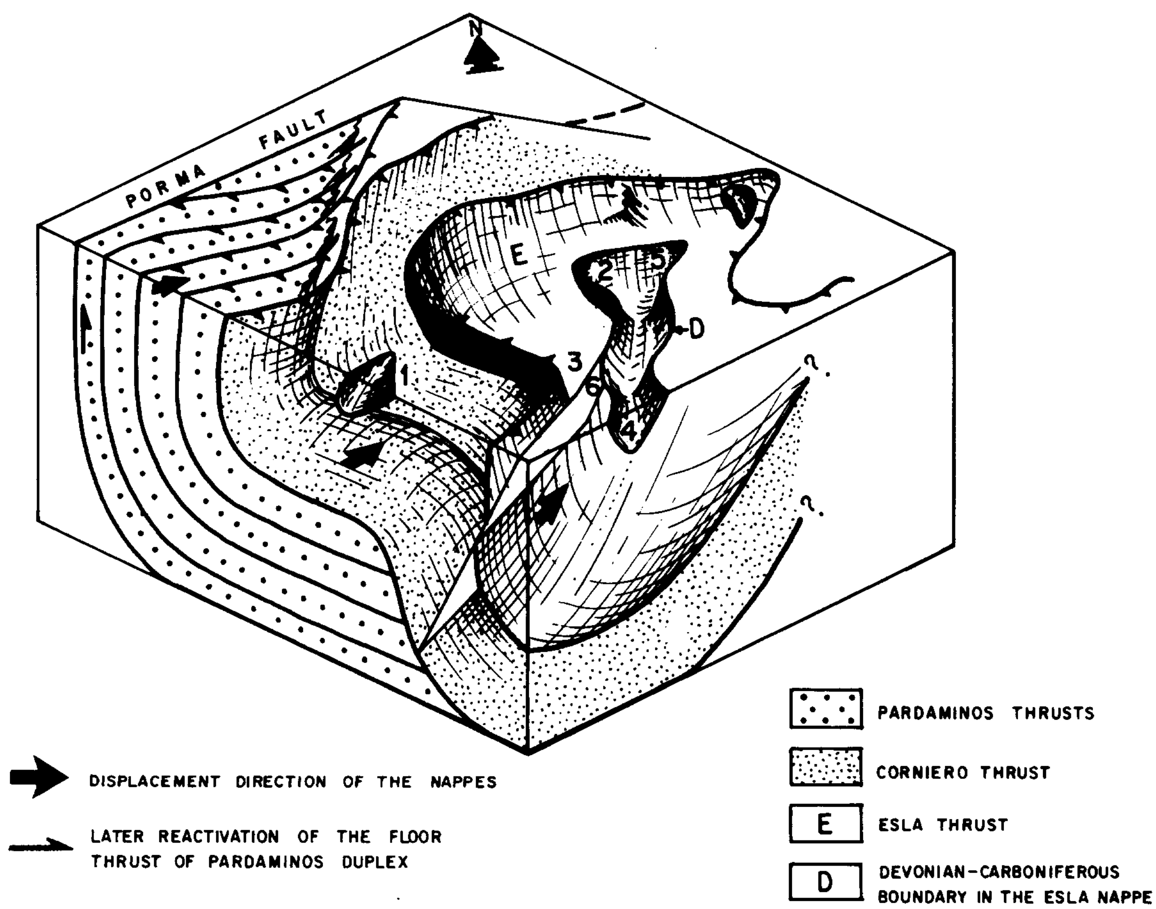


Fig. 6. Present attitude of the structures in the Esla Nappe Region. 1: Felechas Synform. 2: Agua Salio Synform. 3: Peña Rionda Antiform. 4: Peña Quebrada Synform. 5: Peña Verde Synform. 6: Alejico Fault.

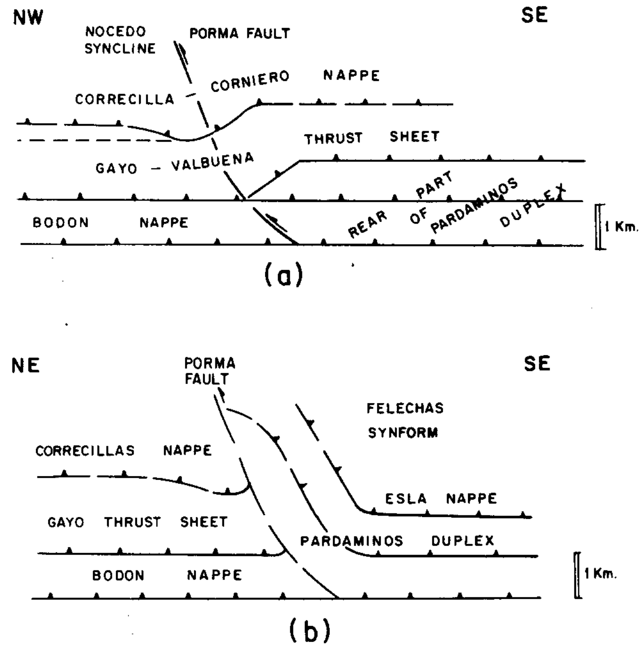


Fig. 7. Two interpretative geological sections showing the movements of the Porma Fault: (a) before movement as a reverse fault and (b) after.

although it is likely that this fold already existed as a lateral structure of the nappes, given that the Pardaminos axial trace undergoes an offset as it crosses the syncline (Fig. 3). Later N–S shortening produced a tightening and reorientation of the frontal and lateral folds, and the vergence of both became southerly with a consequent thrust overturning in the northern limbs of the synforms. The overturning of the Porma Fault, and the Pardaminos Antiform hinge may have occurred at the same time (Fig. 6).

Figure 7 shows the effects of the reverse fault reactivation of the Porma Fault and Fig. 8 the idealized outcrop pattern estimated for the Esla Region in successive deformation stages.

In some places within the Esla Nappe Region an important synorogenic sequence is preserved (Fig. 2). This sequence allows us to determine, with a fair degree of certainty, the age and characteristics of the deformations that progressively modified the earlier structures. Some Carboniferous unconformities cover thrusts and related folds. These unconformable sequences were then deformed, as the folds underwent subsequent tightening. The removal of the effects of tightening shown by

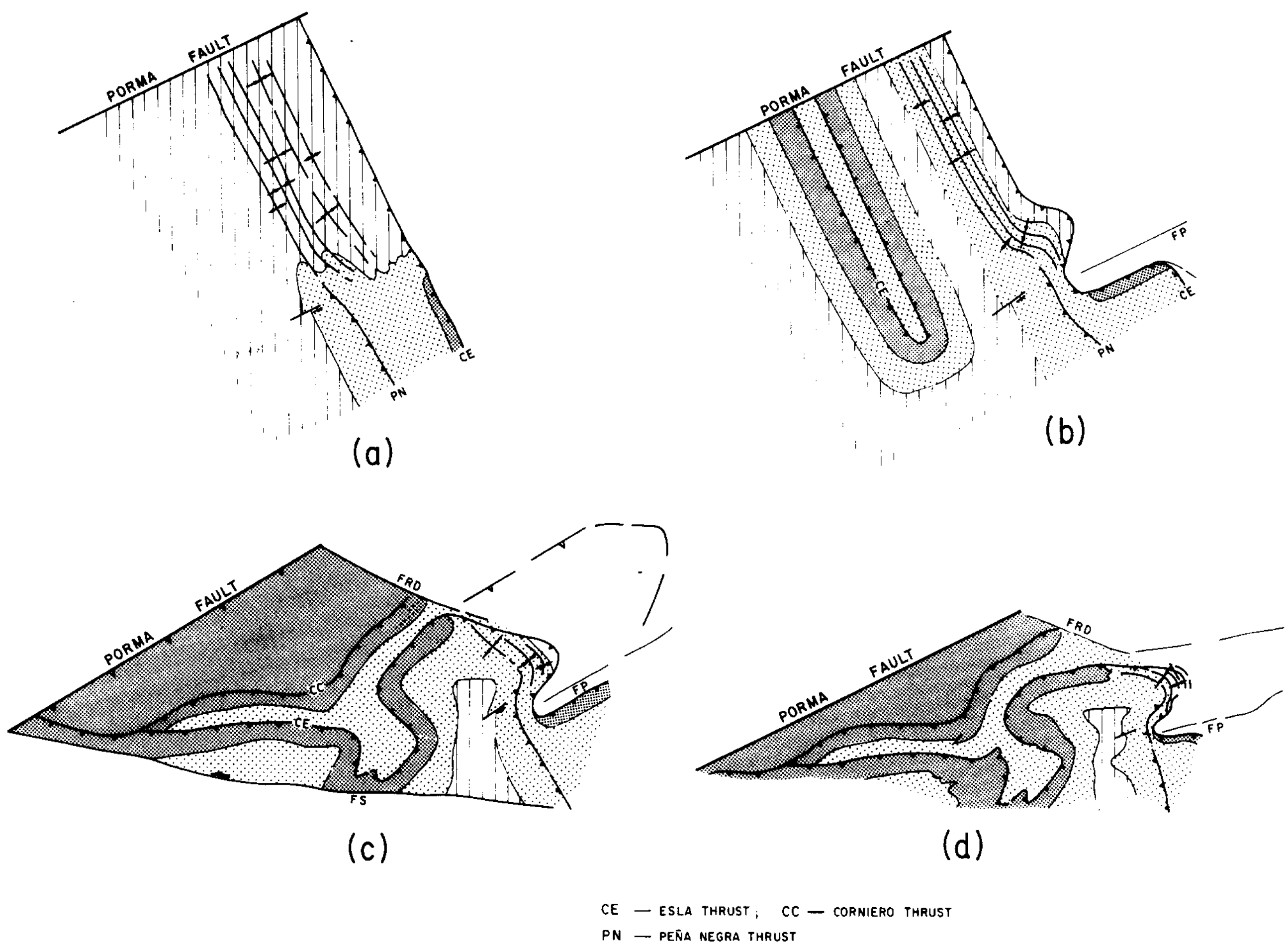


Fig. 8. Suggested outcrop pattern for the Esla Nappe Region during successive deformation stages. (a) After the emplacement of Esla Nappe. (b) After the emplacement of Pardaminos Duplex. (c) After the reactivation of Porma Fault as a reverse fault. (d) Present arrangement (after N–S shortening).

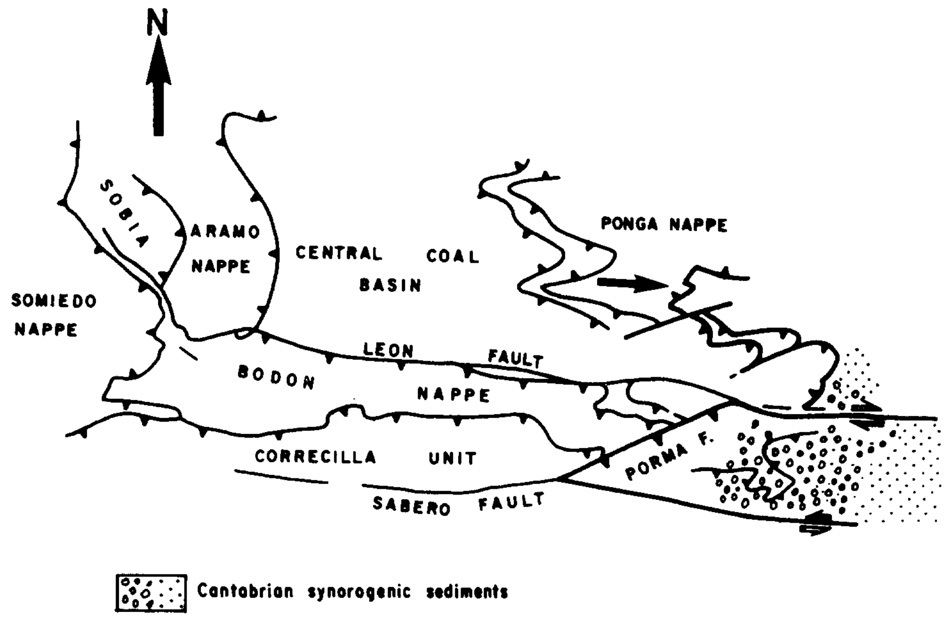


Fig. 9. Proposed kinematic relations between later reverse movement of the Porma Fault and the emplacement of the Ponga Thrust sheets.

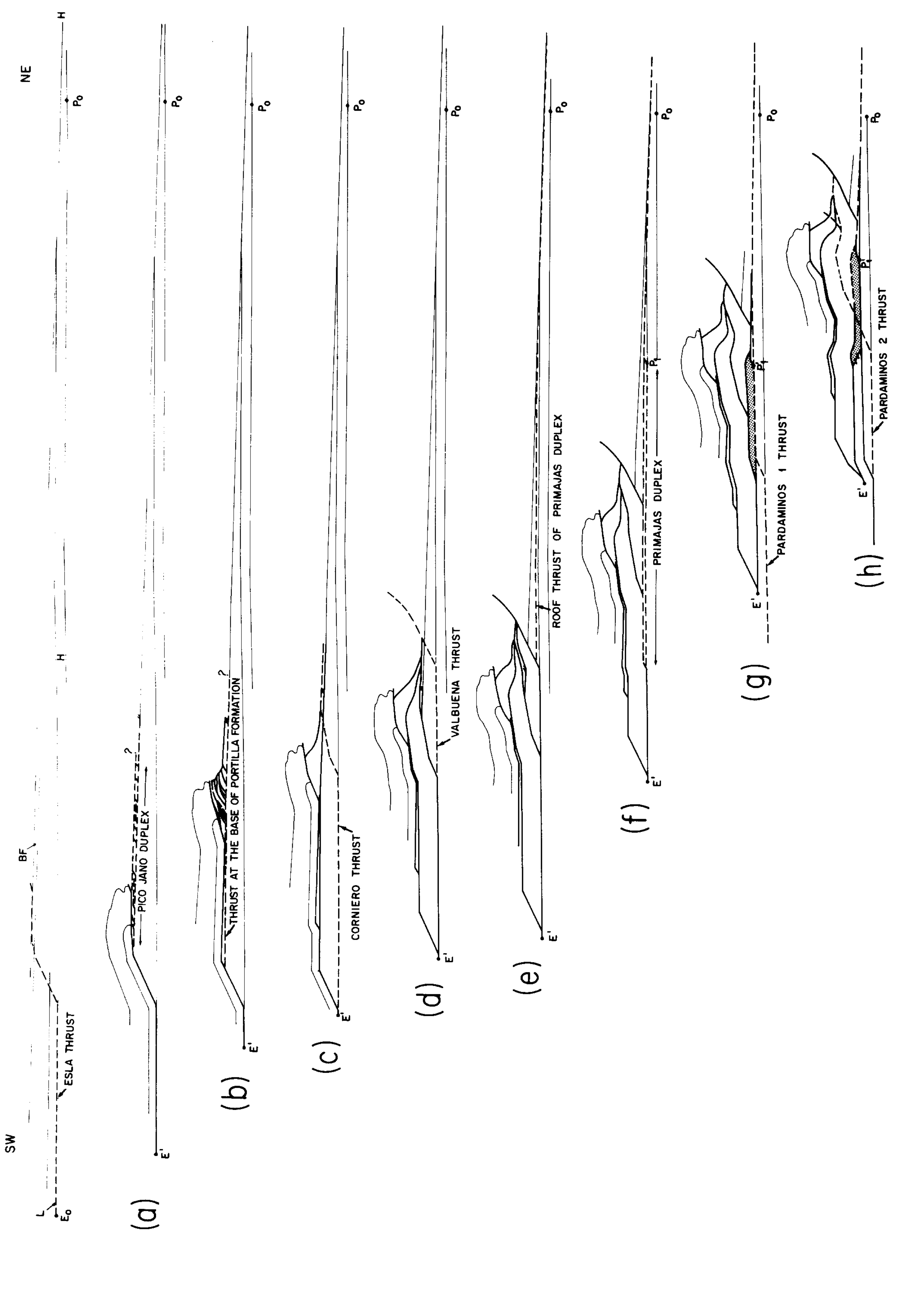
these unconformities leads to a geometry which may be attributed to the initial emplacement of the thrust sheets in the region.

The reactivation of the Porma Fault as a reverse fault is of pre-Cantabrian age (intermediate stage between Westphalian and Stephanian, George & Wagner 1972) and produced an important paleogeographic change in the synorogenic basin, locally reversing the direction of sedimentary transport. The N–S shortening was Stephanian. These deformations and the subsequent erosion give rise to an outcrop pattern in the area nearest to the Porma Fault which is virtually a profile section across the structures (Fig. 6). The fact that the traces of the frontal and lateral structures of the thrust sheets are not now exactly perpendicular is due to N–S shortening; the greater angles (up to 120°) opening toward the north and south. The only fold previously orientated in a N–S direction (the Peña Quebrada Syncline) must have been refolded giving rise to the present sinusoidal axial trace. To sum up, it is only in this synclinal area that there were newly developed E–W folds during the post-nappe deformations; in the rest of the region deformation was expressed in the reactivation and reorientation of older structures towards an E–W orientation. The greater rotation of the lateral nappe structures in the eastern sector accords with the greater degree of shortening encountered (Alonso 1985), which is mainly composed of synorogenic materials with shales predominating over other lithologies.

These later deformations may be interpreted in relation to the convergent emplacement of later nappes in the Cantabrian Zone, which outcrop in the NE of the Esla Region (Fig. 1). The reactivation of the Porma Fault as a reverse fault may thus be related to the emplacement of the Ponga Nappe (Fig. 9). This nappe, was transported to the east (Pérez-Estaún, pers. comm.) and has no tear fault accommodating its displacement at its southern edge. The Leon Fault has a smaller apparent displacement and may be considered as a reverse fault (Aller 1984). As a result, the nappes of the southern arm (Correcilla, Bodón, Esla) must have been transported towards the east or shortened in this direction during the Ponga emplacement, and faults such as that of Porma could have contributed to this shortening as 'back thrusts' (Fig. 9). The N–S shortening affecting the Cea Group of the Esla Nappe Region may also be related to the emplacement of more northerly thrust sheets (the Picos de Europa), in such a way that part of the movement on the sole thrust has been accommodated by synchronous buckling of the southern arm of the Cantabrian Zone. The direction of shortening may be approximately similar in both cases. Moreover, the relationship between these structures may explain the inverted position of thrusts that occurred during the Stephanian in the southern arm of the Cantabrian Zone.

THRUSTING SEQUENCE AND DISPLACEMENT TRANSFER ANALYSIS

Figure 4(a) shows perhaps the only section through the region which meets the conditions for plane strain, because there was no tightening of the lateral folds of the nappes, as typically occurred during deformation subsequent to the emplacement of the thrust sheets elsewhere. The assumption of plane strain is further supported by the fact that the cross-section derived from map data can be easily balanced. This section shows that tightening of the frontal folds of the thrust sheets (the Agua Salio Synform and the Pardaminos Antiform) occurred after the Esla thrust sheets were emplaced. Thus some unconformities truncate the thrust faults, but are themselves folded (Fig. 4a).


SW
NE
ESLA THRUST
BF
H
L
E_o
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E'
PICO JANO DUPLEX
THRUST AT THE BASE OF PORTILLA FORMATION
CORNIERO THRUST
VALBUENA THRUST
ROOF THRUST OF PRIMAJAS DUPLEX
PRIMAJAS DUPLEX
PARDAMINOS 1 THRUST
PARDAMINOS 2 THRUST
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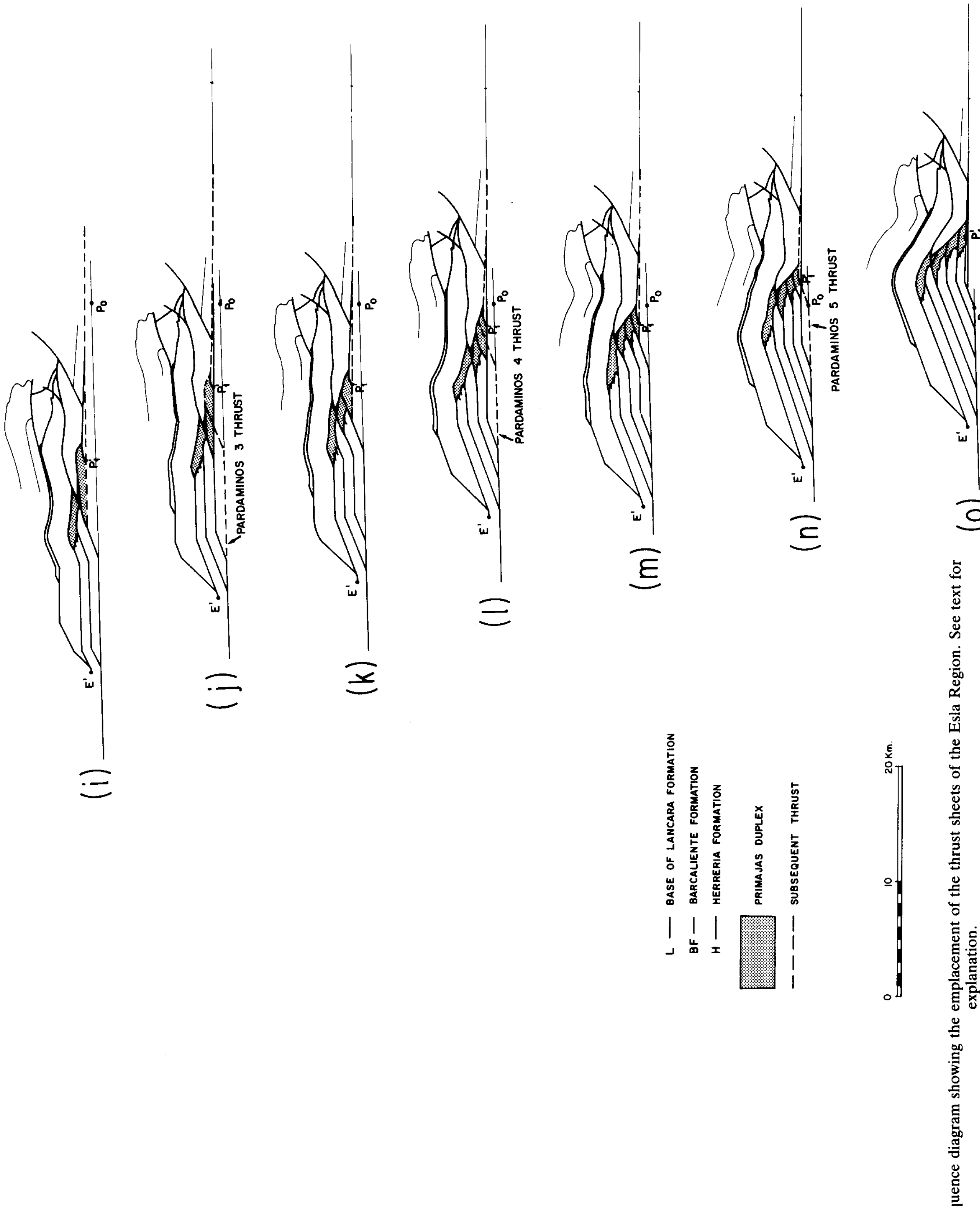

Fig. 10. Hangingwall sequence diagram showing the emplacement of the thrust sheets of the Esla Region. See text for explanation.

The cross-section in Fig. 4(a) has been totally restored (Fig. 4c) and shows clearly the trajectories of the thrusts and the dimensions of the different thrust sheets and sedimentary basins. Using this palinspastic restoration, a balanced cross-section evolution diagram has been drawn up to illustrate the kinematics involved (Fig. 10), assuming a sequence in which thrusts propagate initially into the undeformed area. This kind of sequence may be deduced from several geometric criteria, as will be seen from the following.

Analysis of the Esla Nappe and Pico Jano Duplex displacements

The Esla Nappe is considered to have been emplaced in various stages (Fig. 10b, c & d). A single initial ramp has been postulated (Fig. 10a), which was broken subsequently by two more advanced décollements, one situated at the base of the Alba Formation (Fig. 10b) and the other at the base of the Portilla Formation (Fig. 10c). This sequence is based on the following data.

(a) It is significant that the known cumulative displacement of the Pico Jano Duplex, is equal to the length of the footwall flat in the transport direction, where the Esla Nappe rests on Upper Devonian rocks. This is the flat which separates the footwall ramps of the nappe above and below this stratigraphic level (Fig. 10b). Thus after restoring the Pico Jano Duplex, both ramps come together to form a single one (Fig. 10a). If a forward sequence is accepted, only one ramp, subsequently broken by a more advanced flat (Fig. 11) would be required, whilst in a rearward sequence two initial ramps separated by a flat are needed.

(b) After the Pico Jano Duplex emplacement, a new thrust was developed at the base of Portilla Formation. In a forward direction its displacement was partially accommodated by a thrust which cut across the floor thrust of the Pico Jano Duplex (Fig. 10c).

The translation of the rear of the Esla Thrust (19 km) must have been accommodated by thrusts which make up the Pico Jano Duplex and the Esla Thrust, forward of its branch line with this duplex. The sum of known displacements of the Pico Jano Duplex (10 km), plus the displacement of the Esla Thrust forward of the branch line with the floor thrust of the duplex (6 km), plus the

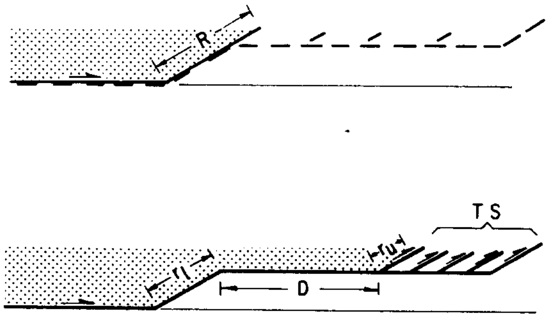

Fig. 11. A primitive footwall ramp (R) is broken in two footwall ramps (r_l and r_u). Cumulative displacement of TS thrust system is equal to the length (D) of the flat between lower and upper footwall ramps (r_l and r_u) of primitive thrust.

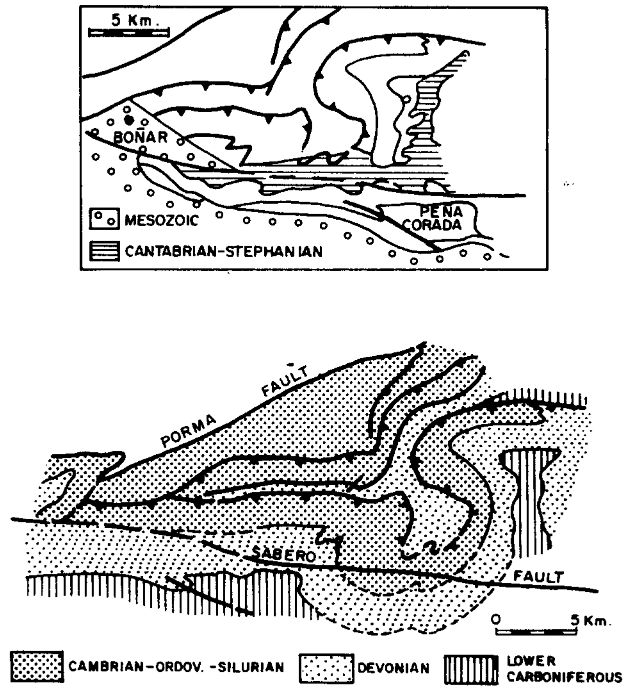

Fig. 12. Estimated outcrop pattern of the surroundings of Sabero Fault before the movement of this fault (modified after Bastida *et al.* 1976).

displacement of the basal thrust of the Portilla Formation (3 km), is quantitatively comparable to the displacement at the rear of the Esla Nappe.

One of the questions to be solved is the position of the lower footwall ramp of the Esla Thrust (r_l in Fig. 11). This ramp cut across the stratigraphic succession from Cambrian to Devonian. According to the displacement postulated for the Esla Nappe, obtained from Huerga–Portilla cut-offs, this ramp should be located under Mesozoic cover around the Porma River (Figs. 2 and 3). Another argument for the position of this ramp is provided by restoration of the Sabero–Gordon strike-slip fault (Fig. 12), using the magnitude and direction of fault displacement proposed by Bastida *et al.* (1976). Once this displacement is restored there is no room between the Corniero Thrust and the Sabero–Gordon Fault in which to include the Corniero and Esla nappes, so that a possible solution would be to place the Corniero–Esla branch line in this sector. In this way, the Lancara Formation translation becomes very similar to that obtained from the Huergas–Portilla cut-off.

Analysis of displacement of the Corniero and Valbuena thrusts

After the rupture of the primitive footwall ramp of the Esla Nappe through the action of more advanced flats situated at progressively lower stratigraphic levels (Fig. 10a, b & c), the flat situated at the base of the Láncara Formation was reactivated, giving rise to the Corniero and Valbuena thrust sheets (Fig. 10c, d & e). The Corniero thrust ramp cuts across the floor thrust of the Pico Jano Duplex and merges with the roof thrust of this duplex, while the Valbuena Thrust cuts across both the floor and the roof thrusts of the same duplex. In spite of its small displacement, the Valbuena Thrust is the best preserved listric fault in the area, and gives rise to the greatest stratigraphical separation.

The Corniero and Valbuena thrust sheets are large horses situated between the two décollements (the roof thrust of the Primajas Duplex and the floor thrust of the Pico Jane Duplex), but they should not be considered a duplex in the kinematic sense, because their displacements are not transferred into the same roof thrust, but rather cut this décollement out of sequence.

The folding and faulting of the floor and roof thrusts of the Pico Jano Duplex, to the west of Pico Jano and to the west of Remolina, were initially caused by a simple shear which affected the whole of the Corniero Thrust sheet, as this duplex is located above the hangingwall ramp of the sheet (Fig. 4a). However, the major part of the present shortening of both the roof and floor thrusts mainly occurred later. This may be inferred from the fact that the unconformities which preserve the Valbuena Thrust from erosion were tilted in the NE limb of Agua Salio Synform.

Analysis of the displacements in the Primajas and Pardaminos duplexes

After the development of the Valbuena listric fault, a new décollement must have been formed over the shaly basal part of the Oville Formation (Fig. 10f). This would serve as a roof thrust when, as a result of the propagation of a new décollement at the base of the Láncara Formation, it gave rise to the Primajas Duplex (Fig. 10g). The kinematics of the Primajas Duplex correspond to that of a typical duplex, in accordance with the model of Boyer & Elliot (1982), with the qualification that its floor thrust is broken owing to the out-of-sequence action of the Pardaminos Thrusts. These utilize the interior thrusts of the Primajas Duplex, reactivating them with the displacement being transferred to the roof thrust. The Pardaminos 2 Thrust (Fig. 10h) took advantage of the footwall ramp of the overlying Corniero Nappe in such a way that one half of the Primajas Duplex was displaced with respect to the other (Fig. 10i). In each hangingwall ramp of Pardaminos thrust sheets the floor thrust of the Primajas Duplex is folded and faulted, probably as a result of simple shear which affects the whole of the thrust sheet (c.f. Ramberg 1959, Ramsay 1980, Ramsay *et al.* 1983).

The amount of duplication of the Herrería Formation within each thrust sheet of the Pardaminos Duplex indicates a far greater translation than would be inferred from the Lancara Formation over the Primajas Duplex (Figs. 2 and 4a). This implies that part of the displacement must have been transferred to the floor thrust of the Primajas Duplex, reactivating it (Fig. 10h, j, l & n). In Fig. 10 the sequence of the two displacements of each of the Pardaminos Thrusts is assumed to be similar to that of the Esla Thrust and to the floor thrust of the Pico Jano Duplex from its branch line. Firstly the Herrería Formation was thrust over the Primajas Duplex (Fig. 10i, k & m) to be followed by the Pardaminos Thrusts carrying the Herrería Formation over a footwall flat situated above the same formation, thus pushing the Primajas Duplex forwards (Fig. 10h, j, l & n). To summarize, the roof and floor thrusts of the Primajas Duplex have acted as the roof thrust of the Pardaminos Duplex for each of the thrusts. In the case of the Pardaminos 2 Thrust, part of its displacement was transferred to the Corniero Thrust, dividing the Primajas Duplex into two parts.

The emplacement sequence proposed requires consideration of the behaviour of the two duplexes, each with a similar stratigraphic composition. They were emplaced successively; firstly the Primajas Duplex (Fig. 10g), then the Pardaminos Duplex (Fig. 10h & o). There exists, however, a more complicated solution for the assembly of these duplexes. It may be speculated that the movement in which the Pardaminos Thrusts have been accommodated into the floor thrust of the Primajas Duplex did not result in its translation as an earlier duplex. In effect, such a movement could have generated some of the horses of the Primajas Duplex, in the same way as the movement of the Esla Nappe over the Upper Devonian flat was inferred to be coeval with the generation of the Pico Jano horses (Fig. 10b). In order to resolve these alternative models it would be necessary to determine the displacement transferred by the sum of both duplexes both forwards and backwards. According to the first model the displacement of the Pardaminos Duplex is added to that of the Primajas Duplex, but this is not so in the second. It is not possible from the mapping to determine this overall displacement, although it must be pointed out that the emplacement of the hindmost horses of the Primajas Duplex, located to the rear of the Pardaminos 1 Thrust, cannot be explained by the second model.

Displacement and shortening arising from the emplacement of the Esla thrust sheets

Table 1 shows the displacements of the different thrusts and thrust systems. In total, the hindmost point

Table 1. Displacement of the main thrusts and thrust systems of the Esla Region. Displacement of the Esla Nappe in its rear part is 19.6 km, which is equal to the sum of displacements of the Esla Thrust, plus that of the Pico Jano Thrust, and that of the basal thrust of Portilla Formation

Thrust or thrust system	Displacement (km)	Cumulative displacement
Esla	6	6
Pico Jano Duplex	10.2	16.2
Basal thrust of Portilla Formation	3.4	19.6
Corniero	5.6	25.2
Valbuena	2.1	27.3
Roof thrust of Primajas Duplex (initial displacement)	14.7	42
Primajas Duplex	17.3	59.3
Pardaminos 1	10	
Pardaminos 2	8.3	
Pardaminos 3	7.2	
Pardaminos 4	4.7	
Pardaminos 5	3.6	92.2

Table 2. Dimensions of duplexes and comparison with some other duplexes of different fold belts. Initial length (L_0) and final length (L_1) are given in km

Duplex	Contraction L_1/L_0 ratio	Number of horses
Pico Jano Duplex (antiformal stack)	6/17 = 0.35	12
Primajas Duplex	10.5/28.2 = 0.37	28
Pardaminos Duplex (antiformal stack)	15/56 = 0.26	5
Duplexes of other fold belts (according to Boyer & Elliot 1982)	L_1/L_0	Number of horses
Foinaven Duplex (Moine)	0.29	34
Windows Duplex (Appalachian)	0.36	21
Mt. Crandell Duplex (Rocky)	0.57	6

of the restored cross-section, situated in the Esla Nappe, has undergone a minimum relative displacement towards the NE of some 90 km. The thickening of the pre-orogenic succession, caused by stacking of thrust sheets is between 8 and 12 km, increasing the initial thickness approximately 3 times, although there was important synorogenic erosion.

Table 2 shows the shortenings of the different duplexes and their respective number of horses, together with the characteristics of duplexes in other mountain chains, according to data compiled by Boyer & Elliot (1982). The Primajas Duplex alone is responsible for 17 km and the Pardaminos Duplex for 33 km of translation in the upper thrust sheet (Fig. 10). It is not known for certain whether the sum of these displacements has been wholly transferred ahead of the Valbuena Thrust, as appears in the sequential diagram, or whether it has been partially transferred to the Valbuena Thrust. A total transfer is impossible because this thrust shows much less displacement than the sum of the two duplexes. In either case, the synorogenic basin situated under the Tejerina Syncline must have undergone considerable displacement towards the NE (equal to the cumulative displacement of the Primajas and Pardaminos duplexes at least; Fig. 10a–o), and should be considered as a 'piggy-back' basin.

CONCLUSIONS

The Esla Nappe, situated in the southern arm of the Cantabrian Zone, is underlain by three large duplexes (Pardaminos, Pico Jano and Primajas) and two large horses. The first two duplexes form antiformal stacks. The large horses are the Corniero Nappe and the Valbuena Thrust Sheet. The cumulative displacement of all of these thrusts is of some 90 km and causes a 3-fold tectonic thickening of the pre-orogenic succession, and a minimum translation of at least 60 km for the foreland basin. In this group of thrust sheets, directed northeastward, it may be observed that the geometry of the lower thrusts was responsible for the folding of the overlying thrust sheets, giving rise to two bend folds systems, corresponding to the frontal and lateral culmination walls of the thrust sheets. There is, moreover, another system of frontal folds which accommodates the displacement of the thrusts and in some sectors folds higher nappes which were previously developed.

These duplexes and horses appear superimposed on each other at the present level of erosion, with the upper and more advanced sectors juxtaposed with the more backward ones. This supports the assertions of Bally *et al.* (1966), Coward (1980) and Parish (1984) that younger thrusts, developed at lower levels, may subsequently climb and cut higher-older thrusts or roof into them. In the Esla Nappe Region, thrusts always begin to propagate into foreland by means of a flat, and subsequently develop a ramp. Where this ramp cuts the floor or roof thrusts of higher duplexes, it can almost always be demonstrated that it uses the older thrusts, reactivating them. These thrust ramps usually undergo a partitioning of displacement, transferring part of their displacement to one or various older, higher levels of décollements. This happens in such a way that a lower duplex may have more than one roof thrust, a role played alternately by the floor and roof thrusts of higher duplexes. This partitioning of displacement means that the initial footwall ramp is broken into several footwall ramps, producing a secondary stepped trajectory, which does not occur in the hangingwall ramp.

Displacement partitioning also occurs in ramps which do not cut older levels of décollement. In such cases part of the displacement is transferred to levels of décollement ahead of the ramps, giving rise to a stepped trajectory. In the Esla Nappe, the initial footwall ramp was broken due to progressively lower levels of décollement.

In the Esla Nappe Region, such simple concepts as forward sequence, 'piggy-back' sequence or downward sequence, whilst of fairly general validity, are rarely developed, owing to the existence of thrust ramps which cut higher thrusts, or to low and high levels of décollement acting alternately. Despite this, other rules of more general validity seem to apply, as follows:

(a) thrusts propagated into the undeformed volume;

(b) a certain level of décollement was always propagated forwards;

(c) an initial footwall ramp may be broken by progressively lower levels of décollement.

Following the emplacement of the thrust sheets the deformation probably continued as a result of convergent emplacement (towards the east and south) of later collateral nappes of the Cantabrian Zone, which affected a previously undeformed succession to the north. As a consequence of this, the folds associated with the thrust sheets became tightened and reorientated, while tear faults and lateral ramps acted as steps inducing lateral compression. The unconformities of the synorogenic succession provide information regarding the amount and direction of shortening during and after the emplacement of the Esla Region thrust sheets.

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