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Areal balancing and estimate of areal reduction in a thin-skinned fold-and-thrust belt (Cantabrian zone, NW Spain): constraints on its emplacement mechanism

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Abstract—The Cantabrian zone is a curved thrust-and-fold belt forming the frontal part of the Hercynian orogen in northwestern Spain. The present day structure is the result of interference between different kinds of structures describing the arc and a set of cross folds, showing a radial pattern. Some of the structures can be traced all around the arc, while some others are of limited lateral extent, so that the displacement they produce is transferred to some other kind of structure. Taking into account geometrical data and field evidence on the direction of thrust motion an area-balanced model has been obtained. This model permits the restoration of the Cantabrian zone to its pre-deformed stage, and shows that the areal reduction has been about 50%. Globally considered, the structure of the Cantabrian zone corresponds to a detached and deformed wedge of sediments which was being thrusted and folded as it was being subjected to translation. The wedge before deformation was flat-topped and had a basal backslope, but as it was being deformed a surface foreslope was generated. Slope and thickness evaluations fulfil the required theoretical conditions for the décollement to be possible under compressional conditions. Lack of tectonic denudation at the back, persistence of the basal backslope and the general structure of the belt indicate compression and crustal shortening. Only in the most frontal part of the belt, gravitational gliding of rock slabs took place and chaotic mixtures were formed, contributing to the infilling of the Carboniferous basin in the very core of the arc.

INTRODUCTION

THE CANTABRIAN zone forms a thin-skinned thrust-and fold belt situated in the frontal part of the Hercynian orogen in northwestern Spain (Fig. 1). A peculiarity of the zone is its curved shape and the facing of folds and thrusts towards the core of the arc, giving the impression of a converging motion. But such a motion would produce space problems not observed to happen during nappe emplacement. An alternative explanation not causing space problems was given in a previous paper by Julivert & Arboleya (1984), where it was shown that the nappes were emplaced with a rotational motion.

The aims of this paper are twofold: (1) to develop the conclusions reached in the paper quoted above, in order to give a full geometrical and kinematical model for the Cantabrian zone and (2) to discuss the mechanisms of nappe emplacement, pointing out the constraints from field evidence and restorations.

SUCCESSION OF DEFORMATIONAL EVENTS

The structure of the Cantabrian zone is the result of superimposition of the following kinds of structures: (1) thrust-sheets and contemporary folds (folds into which thrust displacement is transferred), (2) folds more or less longitudinal to the strike of the thrusts but subsequent to their emplacement (deforming the thrust-sheets and contemporary folds) and (3) folds crossing the previous structures at high angles and vanishing westwards.

Structures of groups 1 and 2 give the Cantabrian zone its characteristic arcuate pattern. Structures of group 3 show a radial pattern with respect to the arc. The order of generation is that mentioned above, but the time spans during which the successive groups of structures were generated can overlap to a greater or lesser degree.

For additional information about the geology of the area see Julivert (1071), Julivert & Marcos (1973) and Bastida *et al.* (1979).

THE ARCUATE PATTERN OF THE CANTABRIAN ZONE

The overall pattern of first-phase folds and thrusts can be seen in Fig. 1. On the map, these structures seem to be of limited lateral extent, and in fact some of the structures can only be followed for short distances along strike. For this reason, years ago it was attempted to explain the arc as the result of two deformation phases, giving the E–W and N–S segments of the arc (De Sitter 1965).

Careful analysis of the relationships between structures in different segments of the arc preclude that interpretation. Where structures of different trend replace one another there is a genetic relationship between them, and a displacement transfer from one to the other is observed.

In order to discuss continuity or lack of continuity of structures around the arc, three different examples can be selected. The first is provided by the Laviana and Rioseco thrust-sheets. Both units originated from a curved thrust ending at one extreme in a couple of folds, and they show maximum overlap in their central parts (in the central part of the arc). The motion of both has been rotational, according to the model given by Julivert & Arboleya (1984) (Fig. 2A).

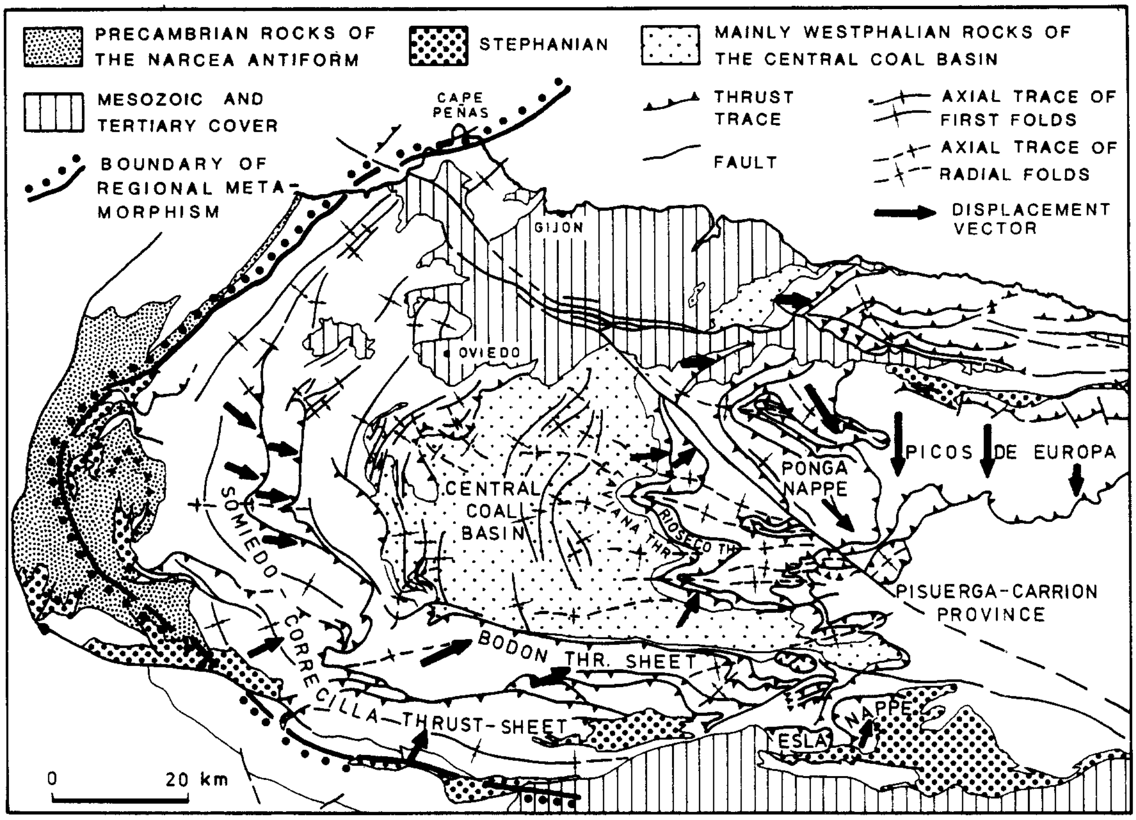

Fig. 1. Geological sketch of the Cantabrian zone showing the displacement vectors for the different thrust units.

The second example is the Somiedo–Correcilla thrust-sheet. This unit considered as a whole has a curved trace, but it is broken into several slices each of which ends laterally in a fold system. This allowed the Somiedo–Correcilla unit to become curved as it was being emplaced (Fig. 2B).

The third example is that of the Bodón thrust-sheet, an E–W trending thrust unit the displacement of which is absorbed by north-northwest trending folds, so that the transformation from a thrust to a fold structure coincides with a sharp trend change. In this case, the displacement transfer helps the structure to curve (Fig. 2C).

In conclusion, some of the structures (thrusts) can be traced all around the arc. Some others are of limited lateral extent but the displacement they produce is transferred to some other kind of structure, so that the arc is described not by an individual structure but by several structures of different kinds, but genetically related.

AREAL BALANCING AND AREAL REDUCTION

For a geometrical model to be realistic, compatibility must exist between the displacement of the different thrust units and between them and those produced by folds, since a displacement is transferred from the thrust-sheets to the folds at their terminations. That is to say, the bedding surfaces in the model have to be area-balanced.

In a previous paper (Julivert & Arboleya 1984) the true trace of the arc, disregarding cartographic effects, was obtained and also the tightening of the arc produced by the radial folds could be evaluated.

Considering the first-phase structures, a shortening (and consequently an areal reduction) of about 35% due to folding can be calculated from balanced cross-sections across the northern part of the fold and nappe province and the Central Coal Basin. If the transformation from fold to thrust structure was like the third example described above in all cases, and if fold axes were parallel, the shortening produced by folding and by thrusting (measured in the motion direction) would be the same, and a 35% areal reduction could be accepted. But because the fold axes are not perfectly parallel all the thrust-sheets have been emplaced with a more or less important rotational component, making the evaluation of areal reduction more complex. Even the Bodón thrust unit must have suffered some rotation, for otherwise its overlap would be smaller than what is actually observed. The motion of thrust-sheets can be decomposed into a translational and a rotational component, which can be considered separately. The translational component can be evaluated from the shortening produced by folds in the folded sector of the arc. By using different kinds of field evidence (Julivert & Arboleya 1984) the direction of the displacement vector can be evaluated for some thrust-sheets (Fig. 1), and also the overlapping amplitude (or at least its minimum value) can be estimated. From these data, the rotational component can be calculated.

Thus, the steps to follow to restore the Cantabrian

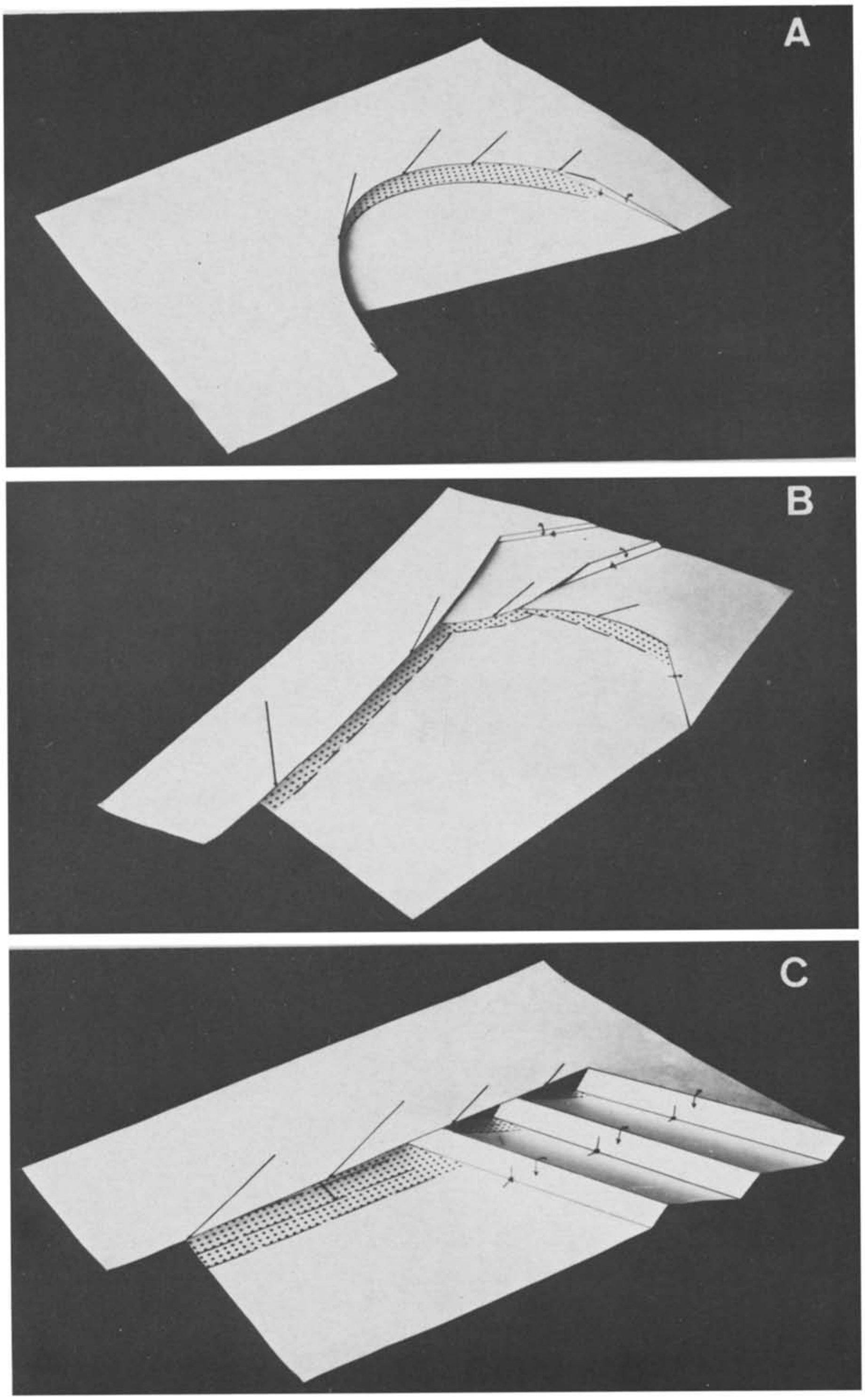

Fig. 2. Models of motion transfer from thrust to folds, with the displacement vectors drawn on the thrust sheets: (A) Model of a curved overthrust ending in a couple of folds: the orientation of the displacement vector changes progressively along the thrust. (B) Model of a curved thrust-sheet broken into several slices: the orientation of the displacement vector changes abruptly from one slice to another and progressively along the same slice. (C) Model of a straight thrust-sheet ending in a set of oblique folds with parallel axes; the displacement vectors are parallel and show an abrupt length change where the thrust crosses a fold couple.

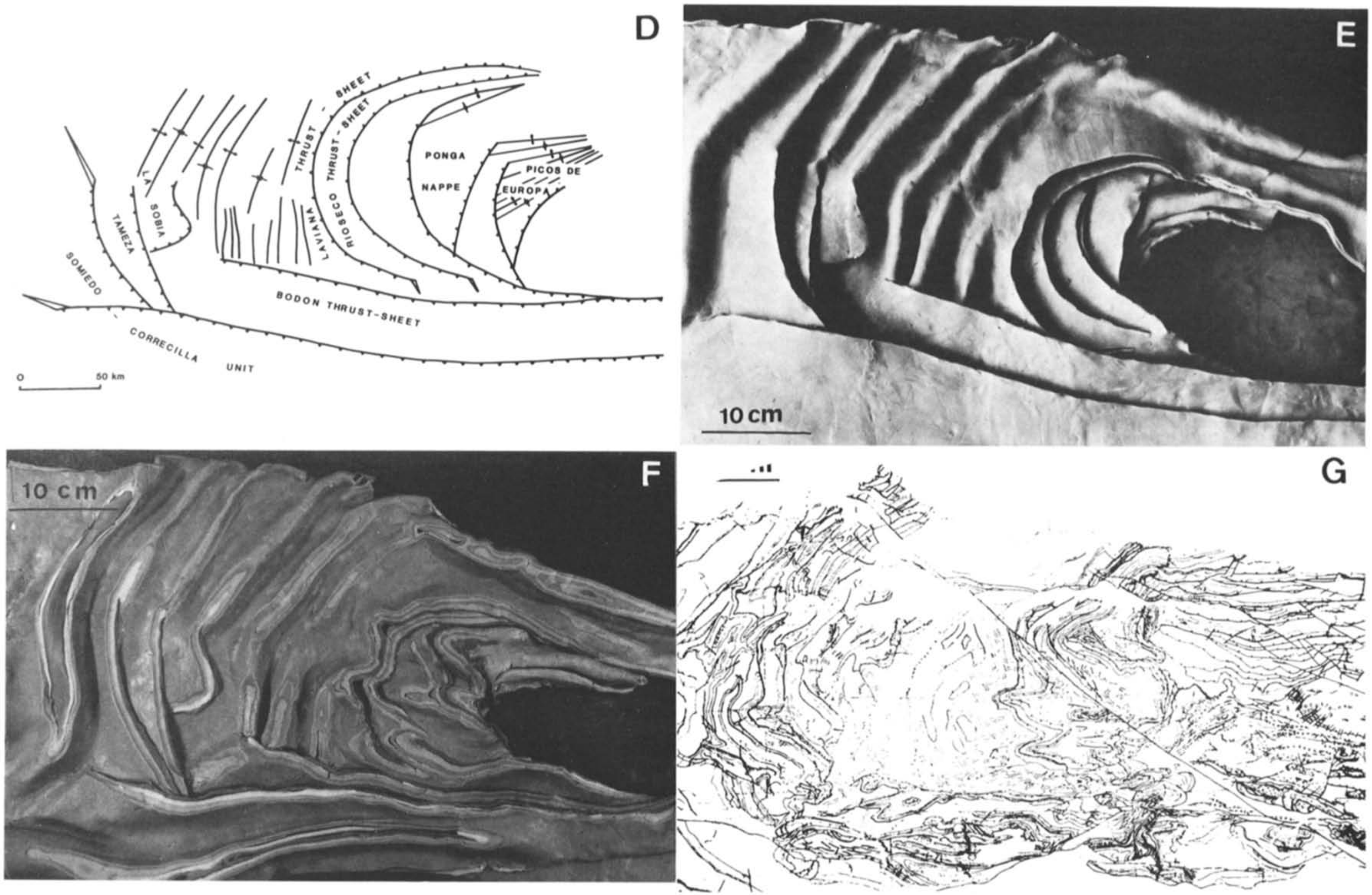

Fig. 2 (*continued*) (D) Schematical restored model of the thrust traces in the Cantabrian zone. (E) Plasticine model of the Cantabrian zone, after thrusting and thrust-related folding. (F) Plasticine model for the Cantabrian zone after radial folding and 'erosion'. (G) Geological map of the Cantabrian zone for comparison with model F.

zone to its pre-deformation state are: (1) to define the true present-day shape of the arc, disregarding cartographic effects due to erosion (Julivert & Arboleya 1984), (2) to unfold the radial set of folds, (3) to translate the thrust-sheets according to the shortening produced by the folds into which its displacement is transferred and (4) to rotate each thrust-sheet according to the field evidence concerning motion direction and overlapping amplitude.

Figure 2D shows the areal restoration of the Cantabrian zone as obtained following the steps indicated above, and Figs. 2E and F show a Plasticine model starting from the restored pattern and following the successive deformational events. In this model it can be observed that no space problems arise from the emplacement of thrust-sheets and that, after 'erosion', the resulting pattern reproduces quite exactly the cartographic pattern of the Cantabrian zone (Fig. 2G).

The model proposed involves an areal reduction of 40–45% after thrusting and associated folding. If later radial folding is also considered, a total areal reduction of about 45–50% can be accepted.

THE MODEL

Among the features of the model proposed, the following can be stressed as the most significant to support its validity: (1) the model is area-balanced, (2) it does not give rise to space problems during thrust-sheet emplacement, (3) when reproduced in plasticine and 'eroded' it gives a pattern similar to the present cartographic pattern of the belt and (4) in the part of the belt where a motion transfer from folds to thrusts is observed, the model implies a greater shortening in the thrusted (southern) than in the folded part, due to the rotational component of the nappe motion.

Points 1, 2 and 3 have been treated above sufficiently. With respect to point 4, it is interesting to compare with data on Palaeozoic stratigraphy, especially with data from the Devonian. From the Narcea antiform towards the centre of the arc the Devonian sequence becomes progressively incomplete (Fig. 3). In general terms each formation has a more restricted extent than the one immediately below, so that the Devonian forms a wedge of sediments thickening towards the convex part of the arc. If the eastern boundaries for the different Devonian formations are traced, the different lines are separated in the folded part of the belt but they converge southwards in the thrusted part. This disposition is also observed if facies distribution is considered. Thus, in the Moniello Formation (Emsian–Couvinian) three types of successions have been recognized (Méndez-Bedia 1976): (1) littoral facies, (2) littoral facies in the upper part and sublittoral facies (coralline) in the lower part and (3) sublittoral (coralline and shelly) facies exclusively. The three types of successions form three well separated parallel belts in the folded part of the arc, but the belts become narrow and discontinuous in the thrusted part.

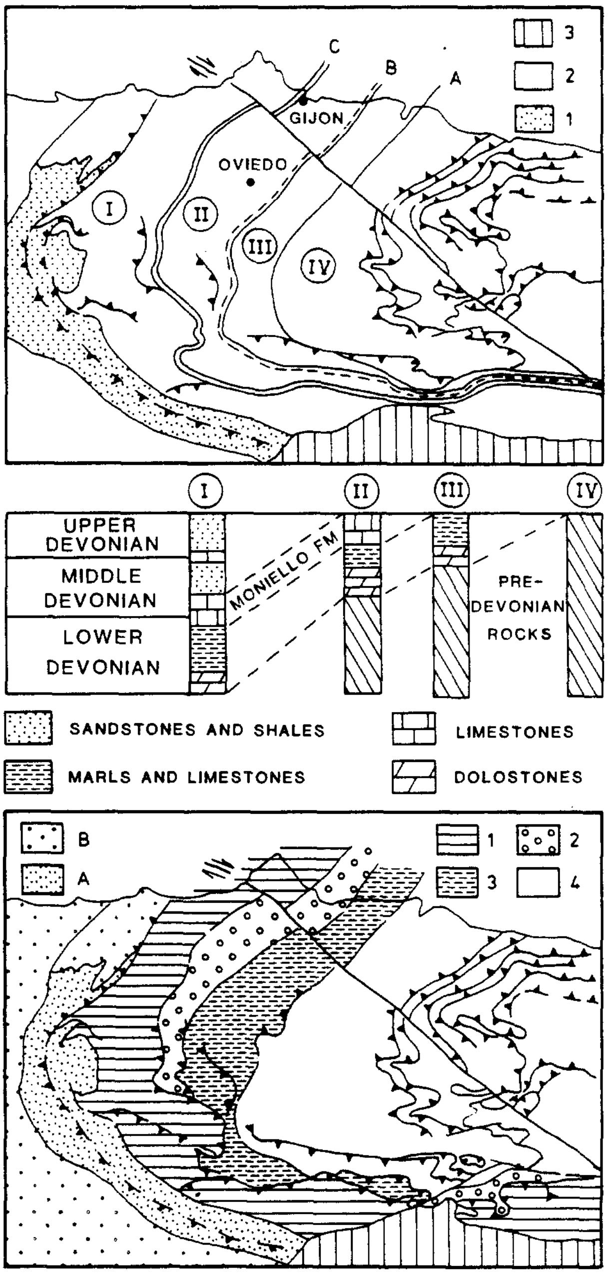

Fig. 3. Distribution of Devonian formations and facies suggesting a greater shortening in the southern than in the eastern part of the arc. Upper part, distribution of the different Devonian formations. (A) Eastern boundary of Devonian sediments. (B) Eastern boundary of the Moniello Formation (Emsian–Couvinian). (C) Eastern boundary of Upper Devonian Sediments. 1, Precambrian rocks; 2, undifferentiated Palaeozoic; 3, Mesozoic and Tertiary. I, II, III and IV locations of the stratigraphic sections below. Middle part, simplified stratigraphic successions in different parts of the Cantabrian zone. Lower part, facies distribution in the Moniello Formation based on Méndez-Bedia (1976). 1, sublittoral facies; 2, littoral facies in the upper part and sublittoral in the lower part; 3, littoral facies predominant through the whole succession; 4, area where Moniello Fm. is not present; A, Precambrian rocks; B, undifferentiated Paleozoic rocks of the West-Asturian–Leonese zone.

EMPLACEMENT MECHANISM: CONSTRAINTS FROM RESTORATIONS AND FIELD DATA

Three mechanisms have been proposed to explain nappe emplacement: gravitational gliding, gravitational spreading and lateral compression. The first requires the existence of slopes and produces extensional structures

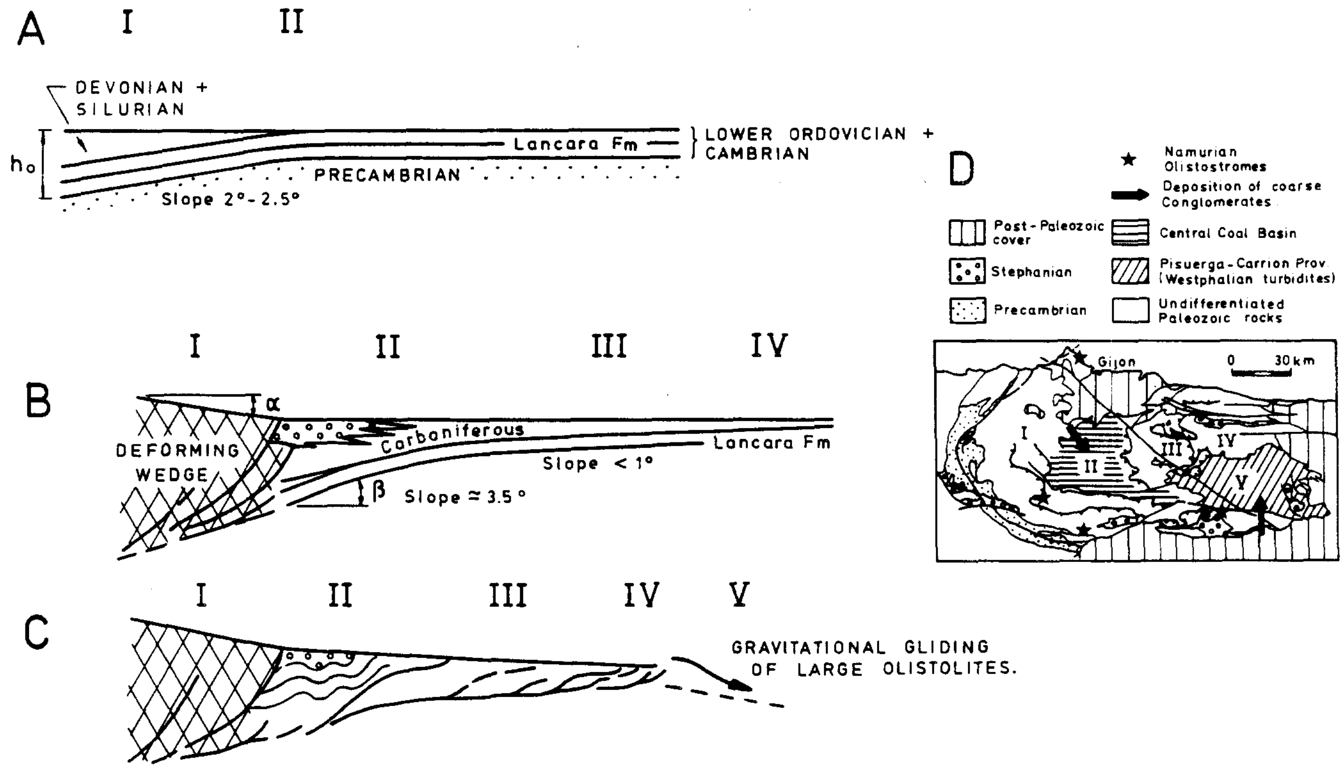

Fig. 4. Sketch showing the evolution of the Cantabrian wedge during progression of deformation (not to scale). (A) Wedge of sediments at the beginning of Carboniferous. (B) The wedge at the Podolskian–Myachcovian boundary. (C) Wedge after the progress of deformation through the whole belt. (D) Structural sketch. I, II, III, IV and V, situation of the different structural provinces represented in sections A, B and C.

at the rear of the sheets. The second requires a rising area with an important strain produced by load at the rear of the thrust units. The third implies crustal shortening. These mechanisms are not necessarily exclusive.

BASAL AND SURFACE SLOPES OF THE DEFORMED WEDGE

Before the deformation started the Paleozoic sequence formed a wedge-shaped prism thickening towards the convex side of the arc (Marcos & Pulgar 1982, Julivert & Arboleya 1984). Just before the first sediments recording instability were deposited (olistostromes) the slope of the detachment level measured from the Central Coal basin to Cape Vidrias was between 2 and 2.5° to the northeast (opposite to the nappe motion) and similar values can be accepted all along the arc (Fig. 4A).

If deformation migrated towards the foreland, as generally accepted and as also supported by field data, the first unit to be emplaced was the Somiedo–Correcilla unit. The timing of thrusting can be fixed as ranging from Bashkirian to the end of Podolskian (lower Upper Moscovian). The evidence is: (1) occurrence of olistostromes in sediments of Bashkirian age, found in the underlying unit (and also transported piggy-back on the unit itself); (2) occurrence of coarse quartzite conglomerates (Curavacas Conglomerate, with pebbles of Ordovician quartzites) of Westphalian B age, in the southern part of the Pisuerga–Carrión province; (3) existence of coarse fluviatile conglomerates (pebbles of Arenigian quartzites and Carboniferous limestones) of Westphalian D age and westerly origin, in the northeastern border of the Central Coal Basin; (4) existence of Podolskian (and perhaps lowermost Myachkovian) beds overridden by the Somiedo–Correcilla unit and (5) existence of Upper Westphalian D/Myachkovian (Uppermost Moscovian) beds resting unconformably on the Esla nappe (eastern extreme of the Somiedo–Correcilla unit) and across its thrust surface (Julivert 1978, Arboleya 1981, Alonso 1982).

With the progress of deformation the sedimentary wedge evolved to a wedge-shaped deforming region. At the same time active deposition was taking place and a thick wedge of terrestrial sediments was laid down in more frontal parts of the belt. A restored cross-section from the Picos de Europa through the Ponga nappe into the Central Coal Basin, at the time of the Podolskian/Myachkovian transition, shows a back slope ranging from less than 1° to about 3.5°, measured at the level of Láncara formation (Fig. 4B).

Concerning the deforming wedge itself, the existence of a forward surface slope is shown by the arrival of terrigenous material in the frontal basin, especially by the coarse conglomerates, indicating emersion and active erosion.

Progress of deformation and growth of the deformed wedge resulted in the folding of the Central Coal Basin and the emplacement of the thrust units of the Ponga nappe province.

In the very core of the belt and overridden by the neighbouring provinces there is a province (Pisuerga–Carrión) in which turbidite deposition took place during Bashkirian and Moscovian time. This was an area of deep-sea deposition and hence a forward slope must have existed connecting the deep-sea basin and the shallow areas around it. The slope around the basin allowed transport of terrigenous material by turbidity currents and the gliding of olistolites, some of them of great size. The material came into the basin essentially from the south, where the deformed wedge approached the turbidite basin. Terrigenous materials coming from the west or from the northwest were trapped by the subsiding Central Coal Basin before reaching the turbidite basin (Julivert 1978). Nothing can be known concerning the slope at the base of Láncara Formation in the Pisuerga–Carrión province, but in any case the slope below all the neighbouring provinces was a backslope.

Strain variation across the belt

In the Cantabrian zone, the body of the thrust-sheets is practically unstrained, even at very short distances from the thrust surface (Julivert & Arboleya 1984). In contrast to the thrust-sheets, the folds into which they die out in strike do show some strain and a weak cleavage. These folds are flattened buckles, with somewhat thickened hinges and boudinaged limbs (Julivert & Arboleya 1984). Strains vary according to the material and to the position within the fold; strains in competent beds forming the limbs of folds are very small.

Because of the lack of strain in the thrust-sheets, a weak basal layer with a yield stress lower than that of the rocks within the sheets must be assumed. This layer is to be found at the base of Láncara Formation (Cambrian) and forms the décollement horizon.

If a line is traced showing the beginning of metamorphism and generalized slaty cleavage, practically all the thrust-and-fold belt forming the Cantabrian zone lies outside the cleaved and metamorphosed area (Fig. 1). The boundary represents a structural front, separating an area with fold and fold-nappe structures involving the upper Proterozoic from a frontal thin-skinned area formed by the thrust-and-fold belt described.

Discussion of the emplacement mechanism

The restorations above together with strain distributions and different kinds of field evidence constrain interpretations on the driving mechanisms. The following points have to be taken into account: (1) the basal slope was opposite to the nappe motion, not only at the beginning of deformation but also during its progression; (2) the areal reduction before radial folding has been evaluated at about 40–45% and extensional structures important enough to balance this reduction have not been observed anywhere; (3) the Narcea antiform is the only area where Precambrian rocks crop out and hence it is the only area from which the Palaeozoic sequence could have peeled off, if gravitational gliding was the driving mechanism for nappe emplacement; (4) the area in which the Precambrian crops out in the Narcea antiform is very small if compared with the areal reduction evaluated for the Cantabrian zone; (5) instead of tectonic denudation, what is observed at the back end of the thrust-and-fold belt is the thrusting of the Precambrian over the Palaeozoic, the thrusts flattening forwards to merge with the general detachment surface of the Cantabrian zone (Julivert 1971, Julivert & Arboleya 1984); (6) no significant strain is observed in the Cantabrian zone and (7) a structural front is found at the back end of the thrust-and-fold belt, outlined by the beginning of metamorphism, generalized cleavage and significant strain in rocks.

At the time when deformation started, the sedimentary prism above the detachment layer was 4500 m thick at its back end (h_0, Fig. 4A); it was flat-topped and had a basal backslope between 2 and 2.5° decreasing towards its frontal part (Fig. 4A). The décollement units had to move up the basal backslope and hence externally applied surface forces have to be invoked. A mechanical model for such a thrust-sheet geometry has been given by Siddans (1984).

The progress of deformation thickened the back end of the wedge and formed a forward surface slope, while the basal backslope was increased. Mechanical models considering this geometry have been given by Elliott (1976a,b), Chapple (1978), Siddans (1984) and Davis *et al.* (1983).

The backslope (β) of the weak basal layer can be assumed to have increased to 3.5°, which is the slope beneath the Central Coal Basin at the Podolskian/Myachkovian transition (Fig. 4B). The wedge thickness (h) can be considered to have been increased to 7000 m. Considering a yield stress $K = 200$ bar for rocks in the thrust sheet and 50 bar for its basal layer ($\chi = 0.25$ in Chapple's equation) and a density $\rho = 2.5\ \mathrm{g\ cm^{-3}}$ which are within the range of values used by Siddans (1984), and substituting in Chapple's equation $\rho g h \alpha + 2K\beta = \chi K$, equilibrium conditions would be reached for a surface forward slope (α) of 0.8° (Fig. 4B). By using values of χ and K similar to those of Chapple for the Appalachians α would be 4.2°.

Model G of Siddans (1984) corresponds to the same geometry. In this model, equation $T_{max} = \rho g h \cdot \sin \alpha$ (Goguel 1984) gives the maximum shear stress at a point situated h metres deep, T_{max} being parallel to the surface, whose slope is α. The shear stress (T_b) on the basal layer of the wedge, with a slope of β, is given by $T_b = T_{max} \cos 2(\alpha + \beta)$ (Siddans 1984). If $\alpha = 2°$, $\beta = 3.5°$ and $h = 7000$ m, $T_{max} = 59.8$ bar and $T_b = 58.7$ bar, which means that if the weak basal layer has a lower yield stress (i.e. $T_c = 50$ bar) there will be a tendency for décollement at this level. This tendency is maintained even for lower α values; equation $\phi = 1/2 \cos^{-1} (T_c/T_{max})$ (Siddans 1984) gives the range of orientations symmetrically distributed at $\pm\phi$ about the T_{max} direction along which the shear stress is higher than the yield stress of the basal layer. In the case of the Cantabrian zone, a slope of $\alpha = 1.7$ ($\phi = 5.3$) is enough to keep the slope of the weak basal layer between the range of values for which

$T_b \geqq T_c$, and hence to make possible décollement at that level.

The above calculations refer to the back end of the wedge at the beginning of deformation. Due to the basal backslope, the weak basal layer was progressively shallower forwards. In consequence, in the Ponga nappe region this layer was too shallow at the beginning to be able to become a detachment level. Nevertheless, as it was translated the wedge was being folded and split into many slices, and deformation propagated forwards through the Central Coal Basin to reach the Ponga nappe region. The thickness of the wedge was increased to about 1200–1300 m at its back end and the Ponga nappe province was pushed forwards and detached.

The thrust surfaces of the different sheets show the typical succession of flats and ramps, so that other décollement levels shallower than the general one do exist. The most conspicuous of them is found in the Viséan shales and radiolarites. This level in the Ponga nappe area was only 2000–2500 m deep, so that it could not move forming large sheets and instead split into an imbricate thrust system. In this way, the imbrications in the Carboniferous limestones in the frontal part of the Ponga nappe can be explained.

Conclusions on the nappe emplacement

The structure of the Cantabrian zone is the result of the detachment of a wedge of shallow water sediments in which deformation propagated from its back end forwards, so that it was being folded and thrusted as it was being subjected to translation. Thus, the problem of the emplacement mechanism can be envisaged considering the wedge as a whole.

The décollement implicates the existence of a weak basal layer. The lack of conspicuous evaporite materials at the décollement level seems to indicate that the basal layer was weakened because of high fluid pressure.

The wedge before deformation was flat-topped, but as it was being deformed it changed to a wedge with a surface forward slope and a basal backslope. The slope and thickness values calculated for the Cantabrian wedge fulfil the required theoretical conditions for the décollement to be possible.

Nevertheless, to produce a real décollement a compression must be applied. The motion of the wedge up slope and the lack of tectonic denudation at the back end together with the structure of the inner parts of the belt indicate compression and crustal shortening.

The cross-section through the whole belt shows progressively deeper crustal levels involved in the structure, from frontal to internal parts. The structure of the belt seems to correspond to a large deformed wedge with a thrust surface at its base, in a similar way as has been shown by the COCORP profiling across the Appalachians (Cook *et al.* 1979, Brewer *et al.* 1981). The wedge is thick at the west, involving metamorphic rocks and becomes progressively thinner towards the east, so that in the Cantabrian zone only the sedimentary unmetamorphosed cover is involved.

Only in the most frontal part of the belt could some rock bodies glide gravitationally, contributing to the infilling of the Carboniferous marginal basins. Nevertheless such large blocks are found only in the Pisuerga–Carrión province, the most frontal of the Cantabrian provinces. They are slabs of layers stratigraphically rather high in the sequence (Carboniferous and Devonian?) and always form chaotic mixtures, never thrust-sheets comparable to the typical décollement units of the Cantabrian zone.

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