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Analysis of kilometric-scale superposed folding in the Central Coal Basin (Cantabrian zone, NW Spain)

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Abstract—The Carboniferous paralic sequence of the Central Coal Basin (Cantabrian zone, Hercynian NW Spain) contains an outstanding example of kilometric-scale superposed folding that allows comparison with previous experimental models. First generation folds have a N–S trend and mainly constitute a fold train of fault propagation folds in which an increase of interlimb angle and an increase in the dip of the axial plane is observed from west to east. A second folding phase gave rise to two types of upright, roughly E–W oriented, superposed folds. The superposed folds generated in general by buckling, but their trend and situation are controlled by lateral ramps of the previous thrusts in many cases. Superposed folds of the first type are the most common and have developed on the limbs of previous folds without folding their axial surfaces. They occur in zones and usually have kilometre-scale hinge lines with syngenetic curved traces. These folds present wavelengths distinctly smaller than those of the previous folds. The second type of superposed folds affect both the limbs and axial planes of the previous folds. These second-type folds are, in some cases, smaller than previous folds, and have developed on closed early folds, but in other cases they are large wavelength folds related to the tightening of lateral ramps of the thrusts.

INTRODUCTION

The analysis of superposed folds, developed as a result of buckle folding of previous fold trains, has been the subject of much recent work and a general scheme has been proposed for the different fold geometries possible as a result of the interference, the influence of previous fold shapes and, in the case of a multilayer, the existence of different orders of buckle folds (Ghosh & Ramberg 1968, Skjernaa 1975, Watkinson 1981, Odonne & Vialon 1987, Ghosh *et al.* 1992, 1993, Grujic 1993). These studies have focused on the analysis of superposed folds as they form in experimental models. In this paper we describe a natural example of kilometric-scale superposed folding developed in the Hercynian orogen of northwest Spain (Julivert & Marcos 1973). The description will allow us to compare this natural example with experimental models and describe some characteristics of naturally occurring superposed folds.

REGIONAL GEOLOGY

The Cantabrian zone constitutes the external zone of the Hercynian belt in northwest Spain and presents a set of thrusts and folds that describe a curved pattern known as the Asturian arc (Schulz 1858, Suess 1885, Julivert 1971a) (Fig. 1). Thrust units are composed of Precambrian to Carboniferous sedimentary sequences, non-metamorphic in general, that are locally unconformably overlain by terrigenous continental Stephanian rocks. The folds longitudinal to the arc are related to the thrusts and change from dominant fault propagation folds west of the Central Coal Basin (Alonso *et al.* 1989) and in the Central Coal Basin (Aller 1986) to fault bend folds east of the Central Coal Basin (Alvarez-Marrón 1990) and in the southern part of the Cantabrian zone (Alonso 1987). Both geological and paleomagnetic data indicate that the formation of the arc was initiated at an early stage (Julivert *et al.* 1977, Ries *et al.* 1980, Perroud 1982, Hirt *et al.* 1992), probably by development of the thrusts with a curved pattern due to lateral or oblique ramps that favoured a greater advance of the units in the southern branch of the Cantabrian zone (Aller 1986, Alonso 1987). A general progression of the deformation from west to east at this stage is deduced from the ages of the synorogenic deposits in the different thrust units (Julivert 1978, Marcos & Pulgar 1982), ranging from Namurian ages in the western and southern part of the Cantabrian zone to Westphalian ages to the east. A second set of structures transverse to the Asturian arc (Julivert & Marcos 1973) developed in the Cantabrian zone as the result of a change to N–S-directed shortening in the last stages of the Hercynian Orogeny. These structures were subsequently reactivated during the important north–south Alpine compression (Alonso *et al.* in press). The transversal deformation gave rise to south directed thrusts, amplified previous folds related to lateral ramps of longitudinal thrusts, originated new buckle folds in some areas and was responsible for a tightening of the Asturian arc to the form that can be now observed (Fig. 1).

The Central Coal Basin, situated in the central part of the Cantabrian zone (Fig. 1), presents a wide outcrop of a thick mainly terrigenous synorogenic Carboniferous succession (Fig. 2c). The succession begins with Westphalian lutites, limestones and sandstones of the approximately 2700 m thick Lena Group, situated on top of the Namurian limestones of the Caliza de Montaña Formation. The Upper Westphalian Sama Group

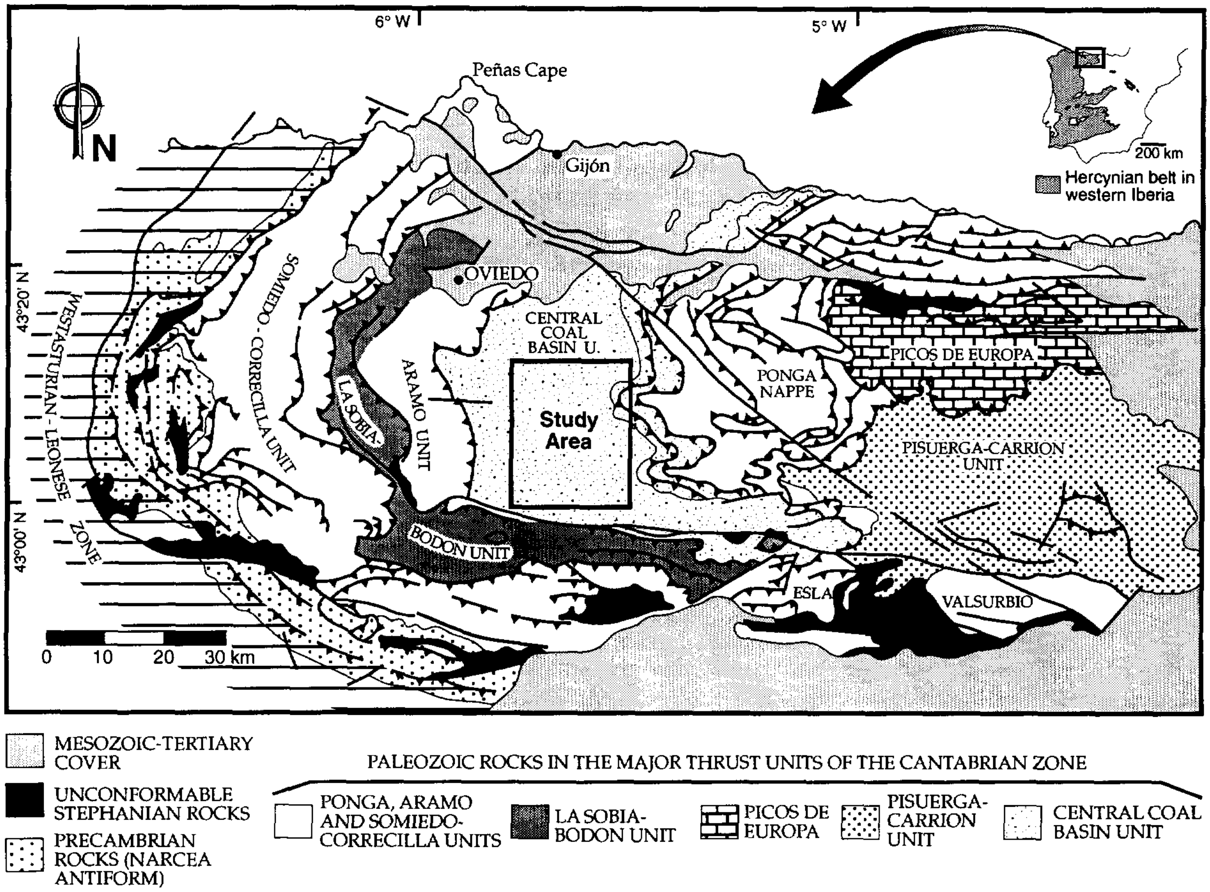

Fig. 1. Geological scheme of the Cantabrian zone with location of the study area. After Julivert (1971a), modified by Pérez-Estaún *et al.* (1988).

lies on top of the Lena Group and is made up of lutites, sandstones, coal beds, some limestones in the lower part and local conglomerates. The thickness of the Sama Group reaches 3000 m in the most complete sections to the north of the study area.

The first generation longitudinal structures are mainly represented in the Central Coal Basin as a N–S-trending fold train that has been interpreted as constituted by fault propagation folds related to displacement towards the east along a basal thrust and associated listric faults (Fig. 2b) (Aller 1986). Recently acquired multichannel seismic reflection data have confirmed this hypothesis (Pérez-Estaún *et al.* 1994). Longitudinal folds change from tight E-vergent folds in the west to open upright folds in the east (Figs. 2 and 3), and this change can probably be related to the existence of a push acting from the west (Aller 1986). The dominant wavelength of the fold train is about 4–5 km.

The second generation transversal structures are mainly E–W-trending upright folds that deform the previous longitudinal folds and constitute an outstanding example of natural kilometric-scale superposed folding. Some characteristics of the Central Coal Basin interference pattern support the regional interpretation referred to above about transversal deformation post-dating, in general, the development of the longitudinal folds, and the axial surfaces of some longitudinal folds are folded by transversal folds (Fig. 2a). The amplification and propagation to the west during transversal deformation of fault bend folds associated with lateral ramps in the eastern Ponga nappe area (Alvarez-Marrón 1990) induced some features of the superposed deformation in the Central Coal Basin, as shown by the major changes observed in the trend of the longitudinal folds (Fig. 2a). The termination to the south of the eastern longitudinal folds and the exclusive presence of materials of the Lena Group in the southwestern corner of the area in Fig. 2a is due to the presence of a lateral ramp oriented ENE–WSW (Alvarez-Marrón 1990) (Fig. 2a). Nevertheless, the transversal folds related to lateral ramps of the thrusts mainly correspond to simple monoclinal bending folds (Alvarez-Marrón in press), and transversal folds showing dominant wavelengths in the study area must be attributed to buckling during the late N–S-shortening. In addition, the geometry of the interference pattern strongly suggests that some longitudinal structures have been unfolded during transversal deformation. It is even possible that the Moreda and Cellón synclines (in the western part of Fig. 2a), constitute an early unique longitudinal structure that was interrupted by the development of a zone with transversal folds. The main features of transversal folds in the study area have been represented in Fig. 3.

After the development of the transversal folds, a local thermal event took place in the southernmost part of the Central Coal Basin, where upper epizone metamorphic conditions are locally reached (Aller 1986). Synmetamorphic deformation during this event gave rise to

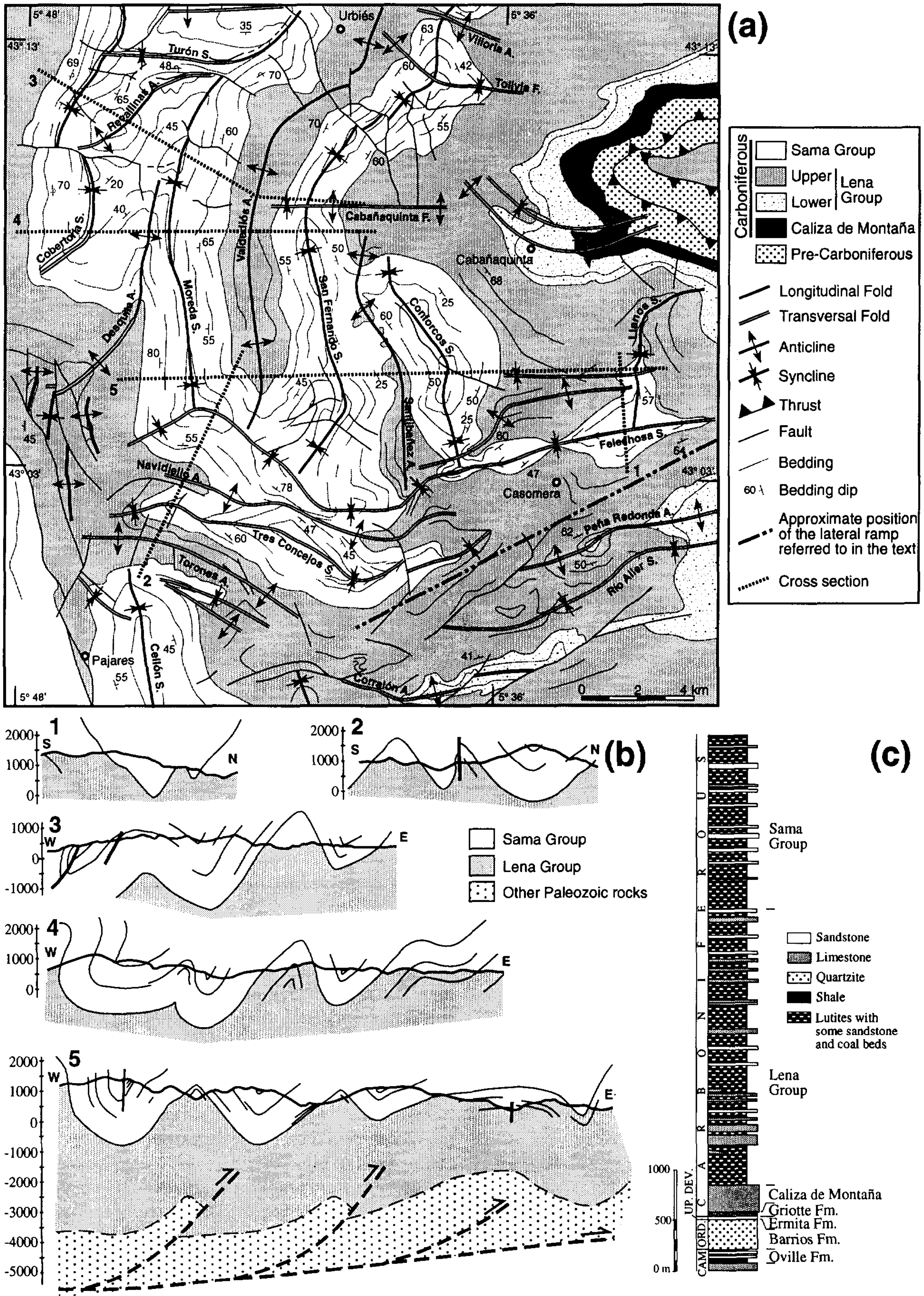

Fig. 2. (a) Geological map of the study area with location of the cross-sections, after Aller (1986) and HUNOSA (unpublished data). (b) Geological cross-sections. (c) Stratigraphic column for the study area.

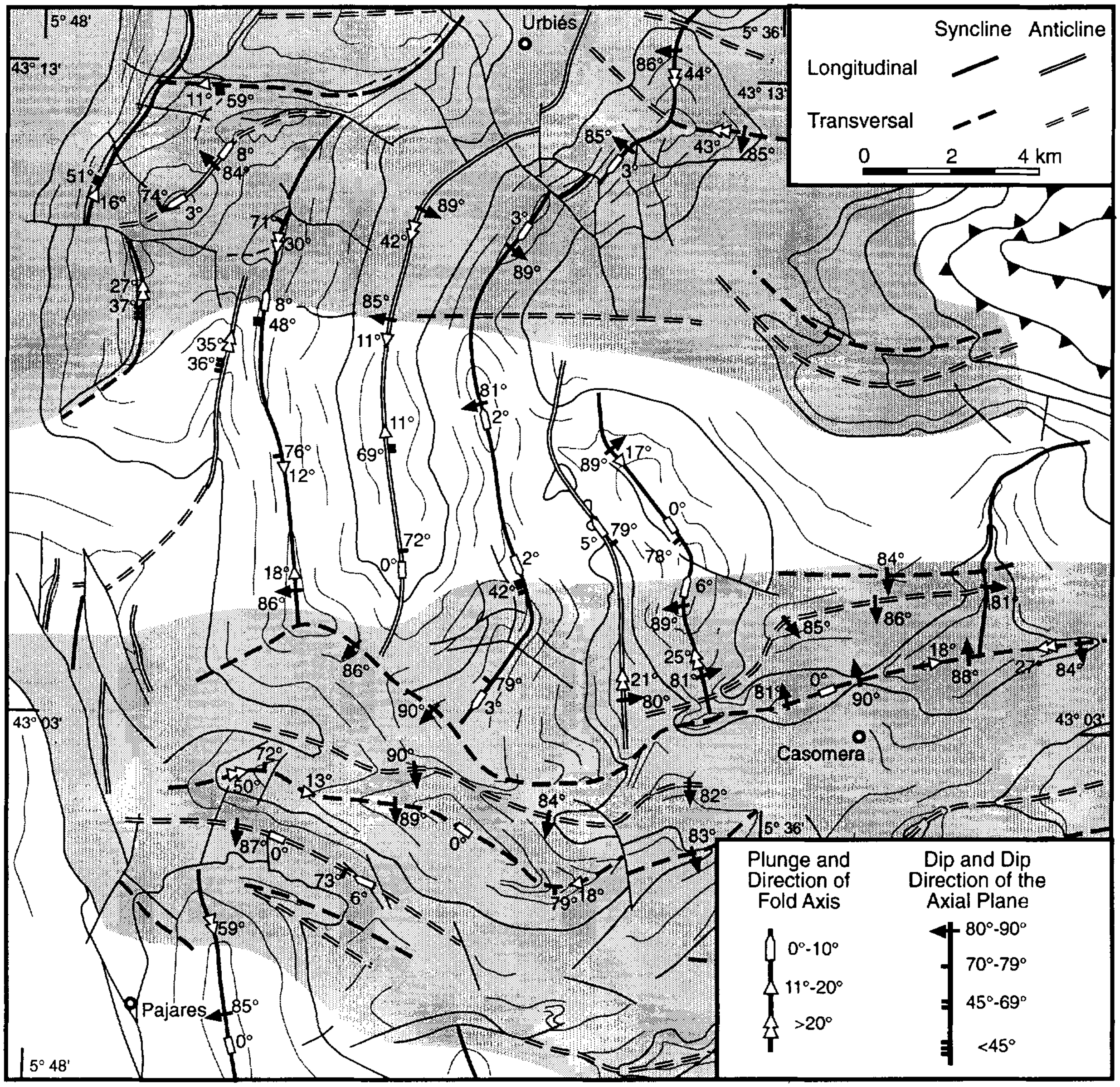

Fig. 3. Attitude of axes and axial planes for longitudinal and transversal folds in the study area. The shaded areas indicate the zones with higher transversal deformation.

metre-scale folds and a non widespread cleavage that usually dips gently to the north (Aller 1986) and post-dates, apart from some local fold retightening, both longitudinal and transversal folds. The development of this cleavage is restricted approximately to the area to the south of the Tres Concejos syncline in Fig. 2a.

THE CENTRAL COAL BASIN INTERFERENCE PATTERN

This study is focused on the analysis of superposed folds in the central-southern part of the Central Coal Basin (Fig. 1), where the best examples of superposed folds can be observed. The analysis of the interference pattern is based on geological mapping by Aller (1986) for the southern part of the study area and on geological data of the National Coal Mining Company HUNOSA (unpublished data) for the northern part. To avoid the influence of the high relief in the area on the geological map the analysis has been carried out on a structure contour (isohypses) map of the contact between the Lena and the Sama groups (Fig. 4). The information represented on the contour map has been obtained from 40 cross-sections through the area that have been completed with the data obtained directly from the map trace of the contact. Some representative cross-sections can be seen in Fig. 2b.

Ghosh & Ramberg (1968) developed experiments of superposed buckle folding and in some of their experiments they deformed layers of modelling clay by compression parallel to the layer first in one direction and then in another. Two basic types of superposed folds were found in the experiments in which the second compression was at 90° to the first compression. These two types of superposed folds were called first-type and second-type superposed folds. Natural examples of these two types of superposed folds can be found in the

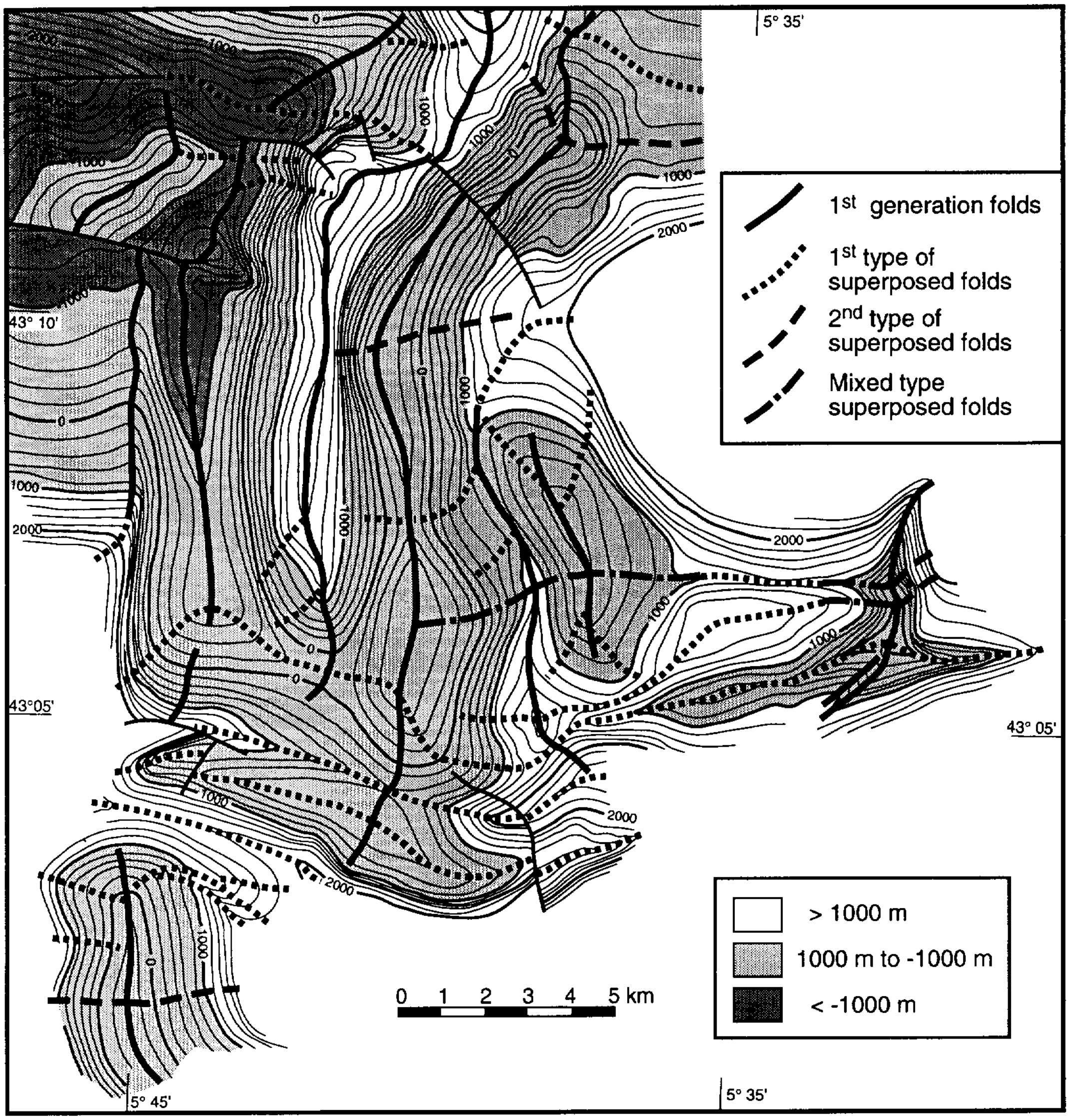

Fig. 4. Structure contour map for the Lena Group–Sama Group contact in the study area with indication of the crest and trough lines of the different fold types.

Central Coal Basin and their characteristics will be described separately.

First type of superposed folds

In the experimental models, these folds develop on the limbs of the early folds and in the hinge zones either die out or go on without significantly distorting the axial plane of the early folds (Ghosh & Ramberg 1968). They are smaller in size than the early folds. Ghosh *et al.* (1992) further subdivided this type of fold superposition. According to their experimental data, previous folds with an interlimb angle greater than 135° give rise to typical dome and basin patterns, while in the case of early folds with an interlimb angle between 135° and 90°, superposed folds are distinctly smaller than the early folds and ride over their hinges. These interferences give rise to domes and basins included in the Type 1 interference pattern of Ramsay (1967).

In the Central Coal Basin, the first type of superposed folds usually form fold trains and give rise to domains with dominant transversal deformation that in some cases unfold longitudinal folds (Figs. 3 and 4). The most important of these domains can be found in the southern part of the study area, where transversal folds develop a dominant wavelength of about 2–3 km. Transversal folds in the outer part of the domain present a relationship with longitudinal folds which is clearly featured in the northern part of the Cellón syncline, an upright fold with an interlimb angle of 80° in the southern part of the map (Figs. 2a, 3, 4 and 5a). The southern superposed folds, located to the south of the Torones anticline, develop on both limbs of the Cellón syncline and die out in its hinge zone. The axial plunge of these first-type folds ranges from 20 to 40° and is lower than the dip of the limbs of the Cellón syncline (45–55°). These folds resulted in unfolding of the Cellón syncline, which gives way to a domain with dominant transversal folds to the north. The northern part of this domain also provides good examples of first-type folds terminating longitudinal folds. The transition to the longitudinal fold train observed further north develops through the first-type Felechosa syncline (Figs. 2a, 3, 4 and 5b), that rides over the limbs of the previous longitudinal folds and, as in the

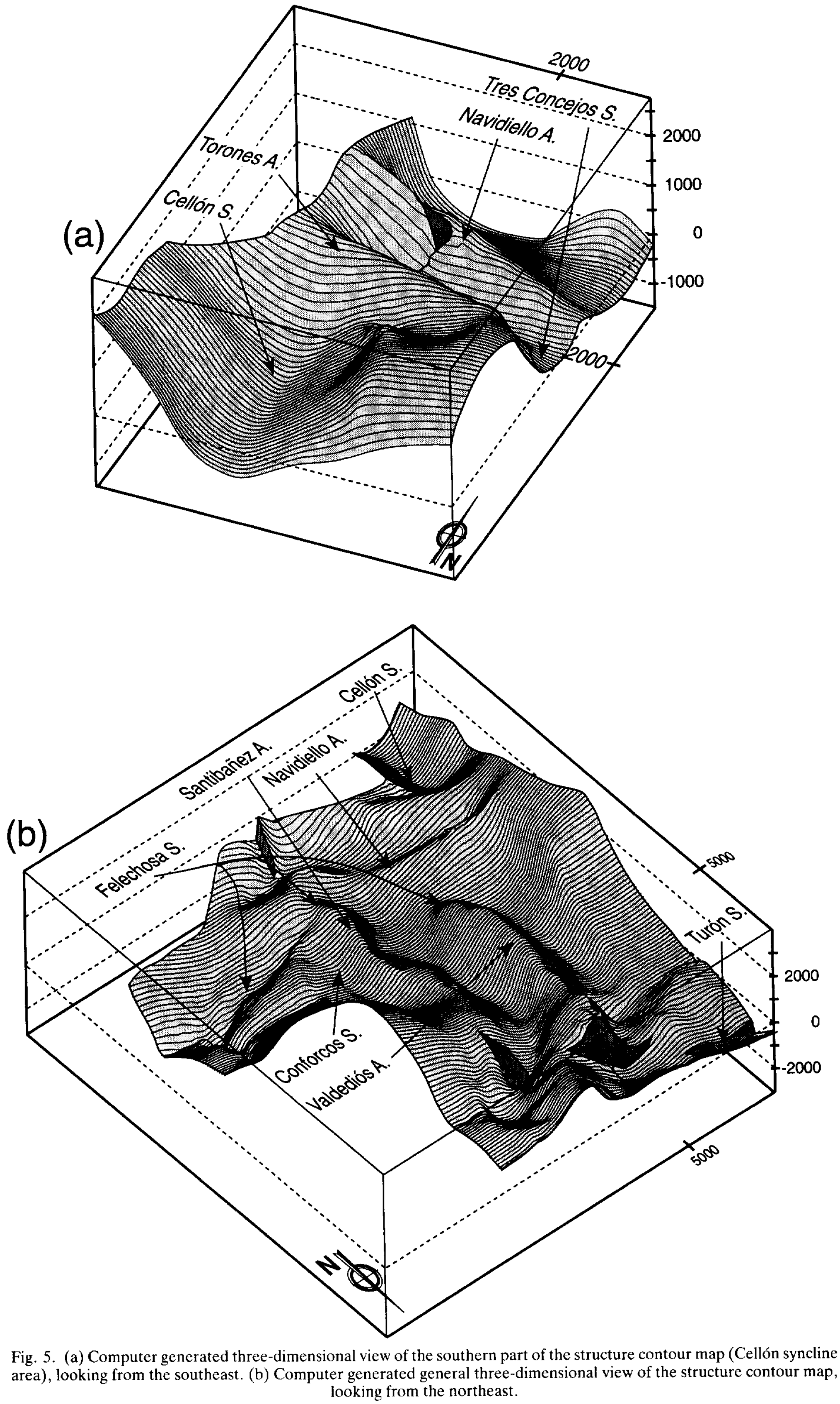

Fig. 5. (a) Computer generated three-dimensional view of the southern part of the structure contour map (Cellón syncline area), looking from the southeast. (b) Computer generated general three-dimensional view of the structure contour map, looking from the northeast.

case of the Cellón syncline, has axial plunges lower than the dips of the longitudinal fold limbs. The southern limb of this first-type syncline unfolds some of the northern longitudinal folds in a similar way to the northern termination of the Cellón syncline. Longitudinal folds affected by the transversal Felechosa syncline possess in general interlimb angles ranging from 80° in the Valdediós anticline to 105° in the Conforcos syncline (Fig. 2b). Nevertheless, the Felechosa syncline also affects the western Moreda syncline, that has an interlimb angle of only 40°.

The first-type folds just described, situated in the outer parts of the domain with strong transversal deformation in the southern part of the zone (Fig. 3), give way to three transversal folds in the inner part of the domain: the Navidiello anticline, the Tres Concejos syncline and the Torones anticline (Figs. 2a, 3, 4 and 5b). It is difficult to assign these folds to a type of superposed folding, since they have low axial plunges (lower than 20° in general) and obliterate previous deformation in some cases. Nevertheless, the fact that these folds present a gradual transition to the first-type folds previously described by increasing fold axes plunge suggests that they can be considered first-type folds. These folds present, in some cases, curved axial traces that cannot be attributed to a later deformation (Fig. 4) and are very similar to curved traces found in first-type folds of some experimental models (cf. Ghosh & Ramberg 1968 Plate II).

Another example similar to the one just described is found in the northwest part of the study area, in the northern part of the Revallinas anticline (Figs. 2a, 3 and 4). This longitudinal fold cannot be continued to the north and its termination is related to the development of a first-type superposed fold with the axial trace oriented E–W, that rides over the eastern Moreda syncline. This termination favours the development, to the north, of the E–W oriented Turón syncline.

The unfolding of an open longitudinal syncline by first-type superposed folds can be observed in the northern and southern termination of the Conforcos syncline in the eastern part of the zone (Figs. 2a, 3 and 4). This upright longitudinal fold has an interlimb angle of about 105°, greater than those of longitudinal folds previously described (Fig. 2b), and has a subhorizontal axis. In this case, the unfolding is also produced by the development of first-type superposed folds, but they are more open and their axial trace makes a lower angle with the axial trace of the longitudinal fold than in the cases previously described (Fig. 4).

A different style of first-type superposed deformation is observed on early folds with interlimb angles of about 40° in the western part of the area. The axial traces of the Desquite anticline and the Cobertoria syncline draw bends in the southern part (Figs. 2a, 3 and 4) that can be misinterpreted as due to the presence of a superposed fold of the second type. Nevertheless, the eastern limb of the Desquite anticline is not affected by any superposed fold, and minor longitudinal folds can be observed in this area that preserve their original N–S orientation (Fig. 2a). According to this, the best interpretation for this fold pattern is the presence of first-type superposed folds that continue the axial trace of previous folds. Similar composite patterns have been described on experimental models by Skjernaa (1975).

Second type of superposed folds

These folds were defined from experimental models by Ghosh & Ramberg (1968) as folds about the same size or slightly smaller than the previous folds that fold together both limbs of the previous fold, distorting its axial plane. Skjernaa (1975) and Ghosh *et al.* (1992) indicated the possibility of wavelengths greater than those of the previous folds in this type of fold superposition. This second type of superposed folds gives rise to folded axial traces included in the Type 2 interference pattern of Ramsay (1967).

Second-type superposed folds with different morphologies can be observed in the interference pattern of the Central Coal Basin. Folds smaller than initial folds are not common. This type of interference is observed in the northeast part of Figs. 3 and 4, where the axial plane of the San Fernando syncline is folded by the Tolivia fold, and in the eastern part of the zone, where the longitudinal Llanos syncline is folded by two transversal folds to the north of the first-type Felechosa syncline. The interlimb angle is about 65° for both the Llanos and the San Fernando longitudinal synclines and both present first-type superposed folds contiguous to the second-type folds just described.

In other cases, the second-type folds have wavelengths greater than those of the previous longitudinal structures (Figs. 3 and 4). These folds are very open and can be followed to the east, in the Ponga nappe area (Fig. 1), where they originated as fault bend folds related to lateral structures of the thrusts (Alvarez-Marrón in press). The most important in this group is the Cabañaquinta fold (Figs. 2a, 3 and 4). This structure produces a local steepening in the eastern limb of the Valdediós anticline. The interlimb angle of the San Fernando syncline and the Valdediós anticline decreases from 80 and 70°, respectively, in the southern part to 55 and 45° in the hinge zone of the Cabañaquinta fold. Another structure of this kind is the fold that affects the axial surface of the Conforcos syncline and the Santibañez anticline. This is a case of a second-type superposed fold affecting first generation open folds. The interlimb angle of these longitudinal structures is 105 and 95°, respectively.

Some superposed folds that ride over the previous fold hinge on one limb (first-type superposition) and deform the previous hinge on the other limb (second-type superposition) have been found in the experimental models (Ghosh & Ramberg 1968) and in natural examples by Julivert & Marcos (1973). This type of folds are also observed on Figs. 3 and 4 in the central-eastern part of the zone. The mixed style of these folds suggests their inclusion in a mixed type superposed folds group, as they cannot be arbitrarily placed in any of the types described. These folds have been labelled in Fig. 4 as mixed type superposed folds.

DISCUSSION AND CONCLUSIONS

The fold interference pattern of the Central Coal Basin resulted from two folding phases in which folds are, in many cases, controlled by thrusts, the dominant structures in the Cantabrian zone. This relation is very clear for the early folds, that have been described as fault propagation folds (Fig. 2b) (Aller 1986, Pérez-Estaún *et al.* 1994). Some of the superposed folds are E–W-trending, large wavelength folds of the eastern Ponga nappe area that can be followed to the west in the Central Coal Basin (Fig. 1). These folds nucleated as fault bend folds associated with lateral ramps of the thrusts of the Ponga nappe area (Alvarez-Marrón & Pérez-Estaún 1988, Alvarez-Marrón in press) and amplified and propagated westwards as a result of the late N–S-oriented shortening. The effect of these folds on superposed folding in the study area is twofold: they bring about changes in the trends of the early folds and they influence the general location of the southern domain with high superposed deformation, that continues to the west of the large Felechosa syncline of the Ponga nappe unit (Figs. 1 and 2a). The development of dominant wavelengths in the areas with higher superposed deformation and the presence of minor transversal folds in the more favourable lithologies of the Lena Group, where isolated limestone and sandstone layers (Fig. 2c) commonly give rise to small scale folds (Aller 1986), suggest that buckling was an important mechanism in the origin of superposed folds. In addition, the origin of these buckle folds may be related to the important Alpine N–S-shortening proposed recently for this zone (Alonso *et al.* in press), and accounts for the fact that superposed folding in the Central Coal Basin can be described in terms of the structures found in experimental models of superposed buckle folding. In fact, the Central Coal Basin provides a kilometric-scale example of some geometries and associations of superposed folds that have been obtained in experimental models.

Superposed folds of the first type are dominant in the area. These usually have kilometre-scale hinge lines with, commonly, curved traces. The curved traces are probably controlled, in the case of the southern domain with superposed folds, by the existence of a lateral ramp (Fig. 2a). Transversal folds in the eastern part probably developed from a bending fold related to the lateral ramp. The disappearance of the ramp to the west gives rise to a change in the orientation of the transversal folds, that in the western part probably follow the zones where the longitudinal folds were more open and first-type superposed folding could develop with less difficulties. First-type superposed folds commonly form fold trains and give rise to domains with dominant transversal deformation that unfold longitudinal folds in some cases. The best example of this relationship is observed in the southern part of the study zone. First-type superposed folds in this area develop a wavelength of about 2–3 km, smaller than the wavelength of about 4–5 km observed for the longitudinal folds near to this area. This lower wavelength of the superposed folds is in agreement with both theorical (Ghosh 1970) and experimental (Ghosh & Ramberg 1968, Ghosh *et al.* 1992) data. First-type folds in the outer part of the domain with higher transversal deformation develop on the limbs of longitudinal folds, have axial plunges lower than the dip of the limbs of the longitudinal folds and usually die out in the hinges of the longitudinal folds. This geometry probably indicates that competent horizons being folded resist stretching and show a tendency to preserve Gaussian curvature close to zero during the formation of superposed folds, as in curvature-accommodation folds of Lisle *et al.* (1990). In some cases, these superposed folds unfold first generation folds and favour the development of superposed folds with gentle axial plunges in the inner part of the domain with higher transversal deformation. The fact that first-type superposed folds occur in bands of superposed deformation is also found in some experimental models (Ghosh & Ramberg 1968) and suggests that when first-type superposed deformation has begun, a lower energy is required for growing of the band by lateral aggregation of folds than for beginning of a new band elsewhere. First-type superposed deformation usually affects early folds with interlimb angles ranging from 70 to 110°. Nevertheless, local first-type deformation is observed on early folds with interlimb angles down to 40°. In these cases, first-type folds do not cross, in general, over the hinges of the previous folds and they give rise to composite folds in which an early fold and a first-type superposed fold are welded together in a unique fold (Skjernaa 1975).

Superposed folds of the second type also appear in the area. In a few cases, they present a wavelength of a few km and develop on first generation folds with interlimb angles ranging from 60 to 70°. In other cases they are large wavelength folds. This second group of second-type superposed folds develop on previous folds with interlimb angles up to 105°.

According to the data presented above, first- and second-type superposed deformation are not limited in the Central Coal Basin to ranges of interlimb angle value of the previous folds as restricted as those found on experimental models (Ghosh *et al.* 1992). Early folds with interlimb angles ranging from 70 to 105° can undergo first- or second-type superposed deformation, and first-type folds on early folds with an interlimb angle as low as 40° are locally observed. The origin of early folds by fault propagation folding (Fig. 2b) induces fast vertical changes of morphology for these folds, and the superposed folding that we have studied is probably influenced by deformation at a lower structural level where early folds do not exist. This influence seems to favour, in general, first-type superposed folding. On the other hand, the presence of large second-type superposed folds deforming open early folds in the eastern part of the area can be related to the presence of bending components in the tightening of fault bend folds related to lateral ramps of the thrusts in the eastern Ponga nappe area (Alvarez-Marrón in press).

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