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Growth and propagation of buckle folds determined from syntectonic sediments (the Ubierna Fold Belt, Cantabrian Mountains, N Spain)

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Abstract—The geometry of syntectonic Tertiary sediments in the Ubierna Fold Belt can be explained using the buckling folding theory. The geometric features of the fold train in the pre-orogenic succession also agree with a buckling process. Each fold grew with progressive and coeval rotation of both limbs, although rotation was asymmetric and greater on the forelimb than the backlimb. The diachroneity of synrotational sequences (progressive unconformities) through different folds indicates that fold propagation migrated towards the foreland; however, the initial folds were tightened during a later deformation stage synchronous with the development of younger folds.

INTRODUCTION

In the last few years, most of the natural examples and theoretical models of synsedimentary folds described in the geological literature are kink folds resulting from hinge migration or beds rolling through axial surfaces as a result of fault-bend or fault-propagation, with increasingly longer fold limbs (Medwedeff 1989, Mount *et al.* 1990, Suppe *et al.* 1992, Shaw & Suppe 1994). The natural examples described in this paper differ from those in that they illustrate the growth of the abovementioned thrust-ramp folds; the geometry of the syntectonic sediments of the Ubierna Fold Belt is an illustrative example of growth and propagation of buckling folds. Buckling is a well-known folding process that results from compression parallel to the layers (Ramberg 1963) and gives rise to regular waveforms whose length depends on both thickness and viscosity or strength contrast between layers (Biot 1961, Ramberg 1964). The natural examples of growth folds described here illustrate the progressive development of a buckling fold train; the geometry of the syntectonic strata allows the fold propagation and amplification to be determined. The resulting data are contrasted with theoretical predictions (Biot 1961) and with results from analogue models (Biot *et al.* 1961, Cobbold 1975, Watkinson 1976, Lewis & Williams 1978).

The outcrop pattern and the quality of the exposures in the area under study have allowed large-scale geometric relationships between structures and coeval sediments to be observed directly in the field. The information obtained from field mapping has been complemented with seismic reflection profiles produced for the hydrocarbon exploration.

GEOLOGICAL SETTING

The study area is at the southern front of the Cantabrian Mountains that constitute the western extension of the Pyrenees (Fig. 1). In the Cantabrian Mountains, a Variscan basement was uplifted and structurally overprinted during the Alpine Orogeny. Overlying this basement block, the Mesozoic cover remained undetached. Most of the Alpine structures are due to reactivation of Variscan structures or tectonic inversion of Mesozoic normal faults (Espina 1994, Alonso *et al.* 1996) developed during an Upper Jurassic–Lower Cretaceous extensional episode related to the opening of the Bay of Biscay.

The structure of the study area consists basically of a fold train, named 'Pays plissé' by Ciry (1939), and the Ubierna Fold Belt in this paper, which involves Paleozoic, Mesozoic and Tertiary rocks (Fig. 2). This fold belt is located in front of a major inverted extensional fault (Ubierna fault) and probably developed as a result of footwall buttressing ahead of it (Fig. 3). On the northern side of this fault, Triassic and Jurassic rocks outcrop, while in the southern fault block the post-Albian Cretaceous rocks unconformably overlie the Paleozoic rocks. The Ubierna Fold Belt constitutes the mountain front of the Pyrenean–Cantabrian range in this area. The essentially undeformed Tertiary sediments filling in the Duero Basin, that is the foreland basin of the Cantabrian Mountains, constitute the southern boundary of this fold belt (Figs. 1 and 3).

In the study area, located in the southern block of the Ubierna fault, a Cretaceous pre-orogenic succession, consisting of fluvial sandstones underlying interbedded

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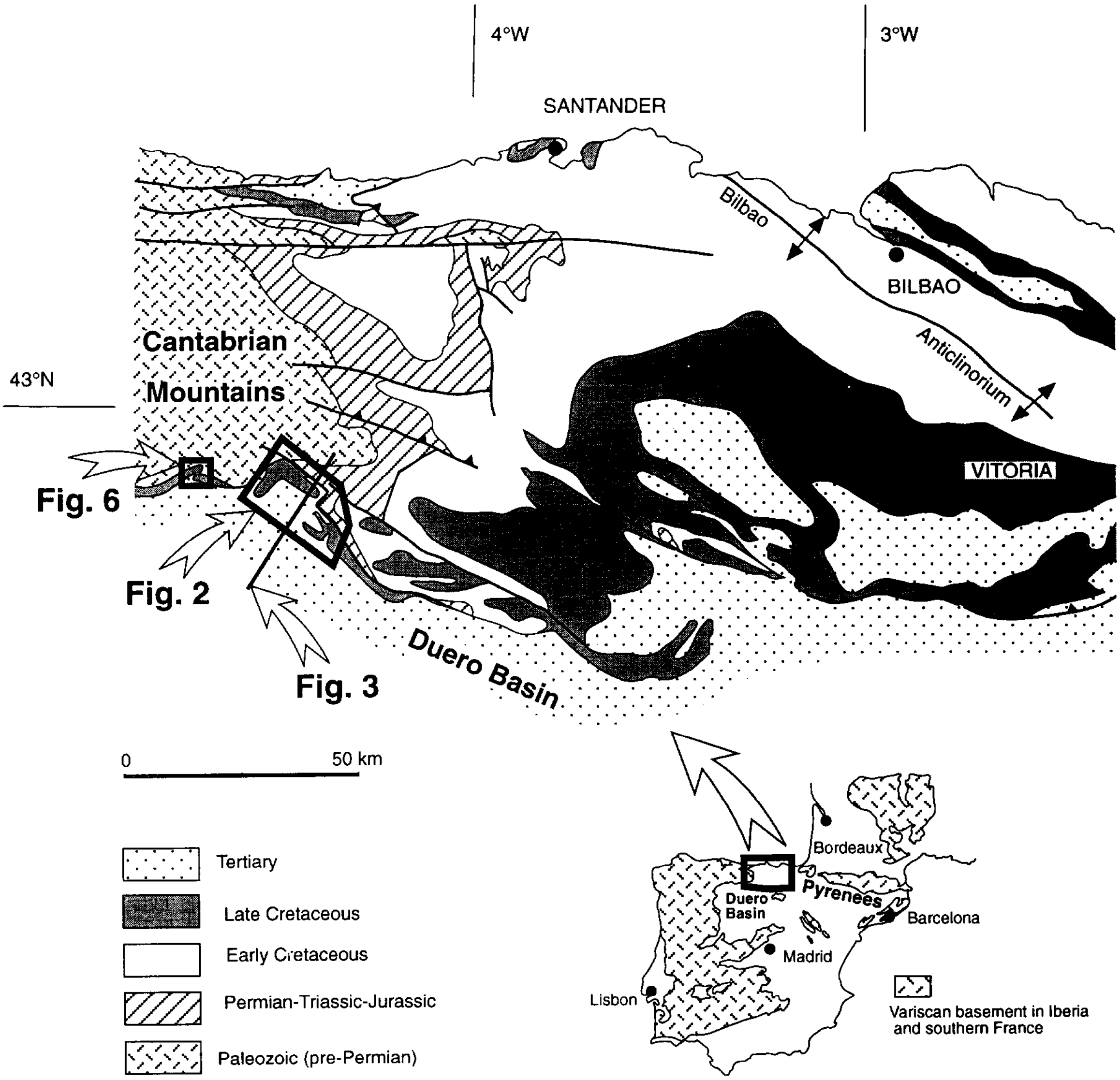

Fig. 1. Location of the study area within the Iberian Peninsula.

shallow marine limestones and marls, lies unconformably on a mainly shaley Carboniferous succession (Fig. 4). A synorogenic Tertiary sequence, mainly consisting of alluvial conglomerates, sandstones and clays derived from the north, overlies the Cretaceous succession (Fig. 2). In the northeastern margin of the basin, close to the Ubierna fault, massive conglomerates constitute the proximal facies of the alluvial fans situated at the foot of the mountain front (Fig. 2). Southwards, the conglomerate beds alternate with siltstones, sandstones and rare lacustrine limestones. Approximately 1000 m above the base of the Tertiary sequence, a level of lacustrine marls and limestones has yielded Late Oligocene ostracods (López Olmedo *et al.* in press).

For chronostratigraphic correlation, bed traces of conglomerates have been considered as isochrons (traces 1–9 in Fig. 2). This assumption is reasonable because the conglomerates show great lateral extent and poor sorting, as expected for a flash flood deposit that can be considered instantaneous on a geological time scale.

THE GEOMETRY OF FOLDS IN THE PRE-TECTONIC SUCCESSION: FOLD MECHANICS

The fold train in the southern block of the Ubierna fault consists of several S-verging asymmetric folds of kilometric scale with a NW–SE strike (Figs. 2 and 5). Geological maps of neighbouring areas (Fig. 6) (Colmenero *et al.* 1982, Ambrose *et al.* 1984) and the seismic sections (Fig. 7) show that the folds deform the basal unconformity of the Mesozoic–Tertiary cover, the fold enveloping surface dipping to the south (Fig. 5). In the pre-orogenic succession, backlimbs dip up to 60°, whereas forelimbs may be overturned by as much as 60°; where overturning is evident, thrusts with omission of strata have developed. Some anticlines show box shapes in the upper part of the Mesozoic succession (Fig. 5). Folds die out laterally, and show relay arrangements with overlapping axial traces in such a way that as a fold disappears laterally the one that replaces it tightens increasingly in compensation. One example of this is the lateral substitution of the Cadéramo anticline by the

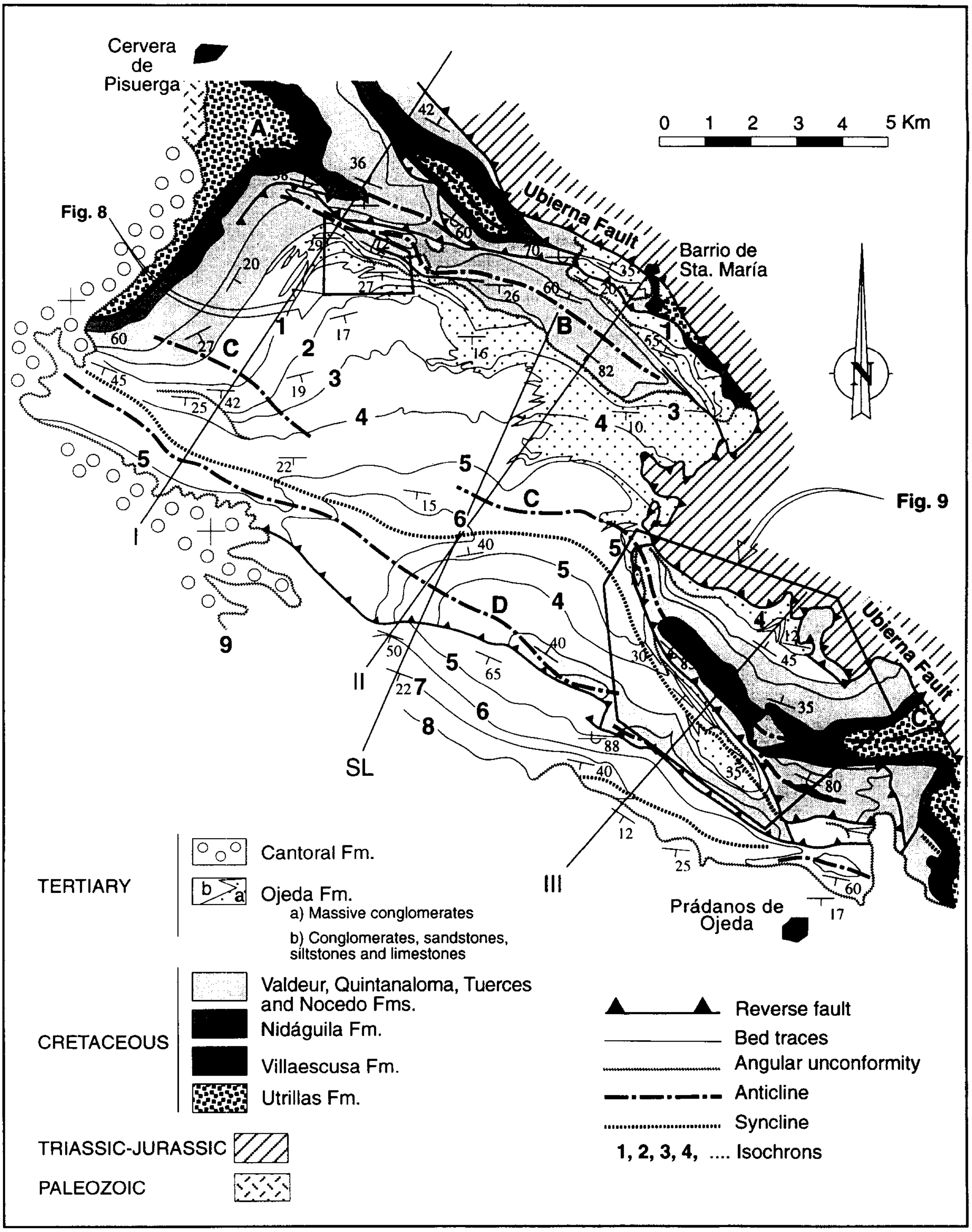

Fig. 2. Simplified geological map of the westernmost part of Ubierna Fold Belt. I, II and III: lines of geological cross-sections of Fig. 3. SL: seismic line of Fig. 7. A, Cadéramo anticline; B, Barrio anticline; C, Villaescusa anticline; C′, Colmenares anticline; D, Santibañez anticline. 1–9, bed traces within Tertiary taken as successive isochrons.

Barrio anticline (A and B in Fig. 2). The overall shortening of the fold train ranges from 1.1 to 1.3 km.

The major folds in the Ubierna Fold Belt show characteristics typical of buckle folding: approximately constant (approximately 3 and 4 km) arclength (initial wavelength) and relay arrangements with overlapping axial traces. This type of folding is encouraged by the presence of a multilayer of well-stratified competent rocks (Upper Cretaceous carbonate formations) over a more incompetent basement (Carboniferous shales and sandstones) both of them jointly deformed. This is responsible for the buckling of the competent succession, while the incompetent basement is assumed to deform by ductile contact strain (Ramberg 1961, Ramsay 1967). When the competent multilayer is thick compared to the dominant wavelength, mullion folds

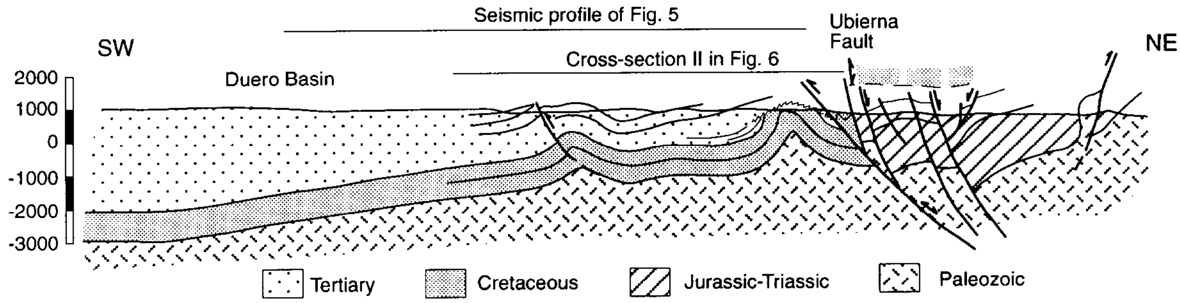

Fig. 3. Simplified geological cross-section showing the overall structure and the geological setting of the Ubierna Fold Belt between the Duero Basin and the Ubierna Fault. Location in Fig. 1.

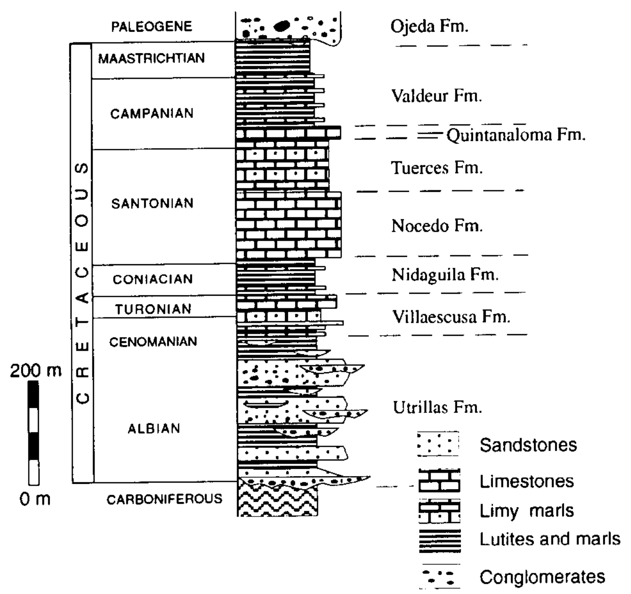

Fig. 4. Synthetic stratigraphic column of Cretaceous Formations in the Ubierna Fold Belt.

occur at the contact between competent and incompetent rocks, i.e. wide round synforms separated by tight antiforms are formed (Fig. 5). In the upper surface of the competent multilayer, fold shapes are also more rounded in the outer than in the inner arcs.

Also supporting the buckling theory is polyharmonic folding, i.e. the development of minor folds where the lithological succession is suitable (as in the case of the Villaescusa formation limestones), as well as migration of the incompetent rocks towards hinges (Nidáguila formation marls), giving rise to Ramsay's class 3 folds (Ramsay 1967); this geometry can be seen as the Cadéramo, Barrio and Villaescusa anticlines (Fig. 5).

The thrusts developed in the overturned limbs can be interpreted as due to the difficulty in accommodating the progressive shortening by amplifying the fold (Fig. 5). An alternative interpretation is that these thrusts have propagated from the basement. However, geological maps show thrusts cutting across competent Cretaceous limestones and dying out downwards. For example, in the Cadéramo and Villanueva de la Peña anticlines (Figs. 2 and 6) thrusts disappear as they reach the Utrillas sandstones and the Nidáguila marls, respectively. Similar thrust–fold relationships can be observed in the seismic sections (Fig. 7).

The folds of Ubierna belt can be interpreted as detached folds over a ductile décollement conditioned by the presence of a thick unit of Carboniferous shales underlying the Cretaceous succession. To the west of the Ubierna Fold Belt, lateral structures occur that can be related to changes in the lithology of the pre-Mesozoic succession (Alonso *et al.* 1994, Marín *et al.* 1995). These lateral structures produce the SE axial plunge of the Cadéramo and Colmenares anticlines.

THE GEOMETRY OF FOLDS IN THE SYNTECTONIC SUCCESSION: THE SYNTECTONIC UNCONFORMITIES

Syntectonic sediments usually display local angular unconformities over anticlinal crest zones as a result of crestal denudation (Rocco & Jaboli 1958, Puigdefàbregas 1975, Millán *et al.* 1994). These unconformities disappear towards the synclines where the sedimentation was continuous. In many natural growth folds, the angular unconformity laterally becomes a bed fan (cumulative wedge system) in the fold profile, as it reaches the syncline hinge zone. The cumulative wedges typically show a dip variation that gives rise to a geometric pattern called single progressive unconformity (Riba 1976a) (Fig. 8). It indicates progressive limb tilting during sedimentation. So, dip changes provide data about limb rotation ages. An angular unconformity developed into a progressive unconformity is known as syntectonic unconformity (Riba 1976a) which is a common feature of many growth folds (Riba 1976a,b, Miall 1978, Anadón *et al.* 1986, Hardy & Poblet 1994).

According to Riba (1976a) the combination of an accelerated uplift of a growth structure followed by a decrease of the uplift generates a composite progressive unconformity (Fig. 8). It is formed by the superposition of two single progressive unconformities; the lower one depicting an offlap attitude while the upper one displays an onlap disposition. Both syntectonic units are articulated by an angular unconformity (Fig. 8). The syntectonic unconformities in the Ubierna Fold Belt differ from Riba's model because no significant progressive unconformity is developed overlaying the angular unconformity (Fig. 5).

In the study area, the diachroneity of fold growth has been determined from the different ages of syntectonic

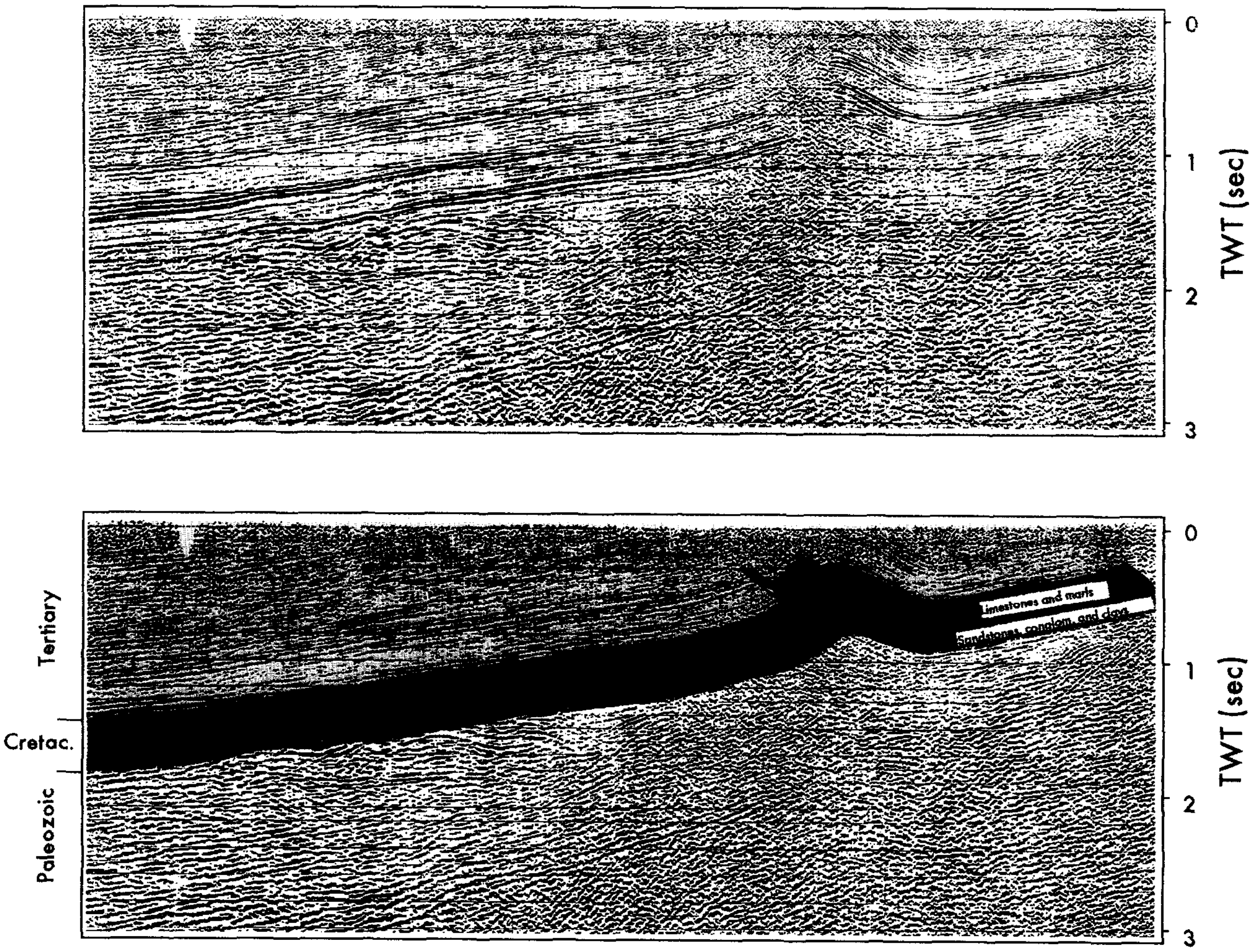

Fig. 7. Time-migrated seismic section across the Ubierna Fold Belt. Section line in Fig. 2.

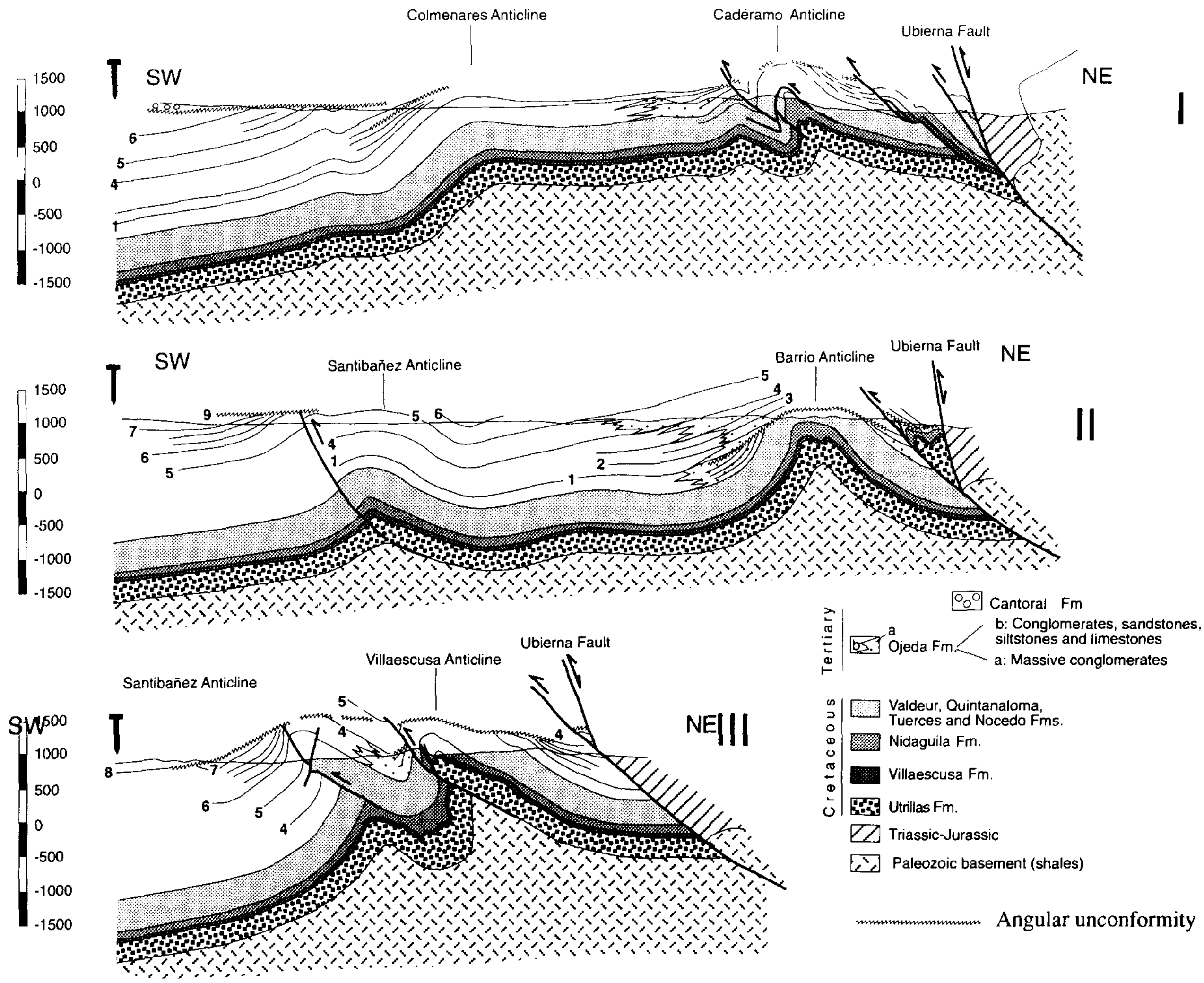

Fig. 5. Geological cross-sections through the Ubierna Fold Belt. Section lines in Fig. 1.

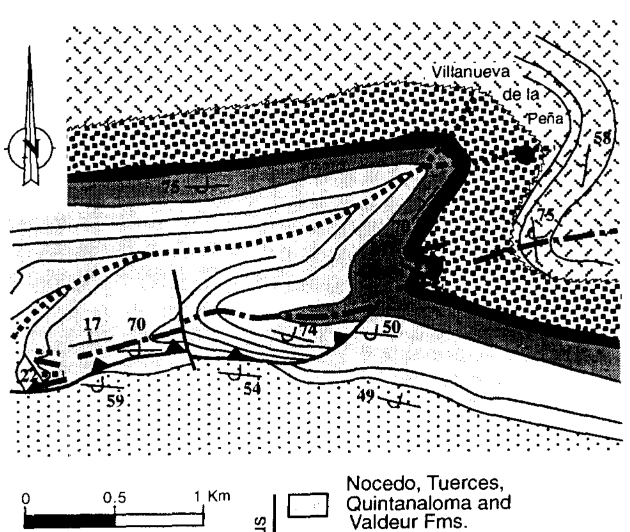

Fig. 6. Geological map of Villanueva de la Peña folds involving Paleozoic, Mesozoic and Tertiary rocks. Structural legend as in Fig. 2. Location in Fig. 1.

unconformities linked to them. The earliest syntectonic unconformity in the area is visible on both limbs of the Barrio anticline (B in Figs. 2 and 5). The outcrop pattern of the syntectonic unconformity developed in the southern limb of this fold is shown in Fig. 9. It consists of a progressive unconformity, up to 450 m thick, overlapped by an angular unconformity whose tip line is at the isochronous horizon 1. The angular unconformity is onlapped by a succession some of whose terms (isochron 2) lie on the fold hinge area, due to the paleorelief, on Mesozoic rocks (Figs. 2 and 5). Although rotation of both limbs occurred synchronously, in the succession underlying horizon 1, it is greater on the southern limb (80°) than on the northern limb (35°). The beds overlying the angular unconformity show a weak progressive unconformity between horizons 3 and 4 (6° rotation at the S limb). Once horizon 6 was laid down, a maximum rotation of 27° occurred at the southern limb and a less marked rotation took place at the northern limb.

The second syntectonic unconformity is associated with the Villaescusa and Colmenares anticlines (C and C′ in Fig. 2, and Figs. 5 and 10). Here the progressive unconformity lies between levels 1 and 4, the latter already being an onlapping level above the angular unconformity (Fig. 10). In the hinge zone, the unconfor-

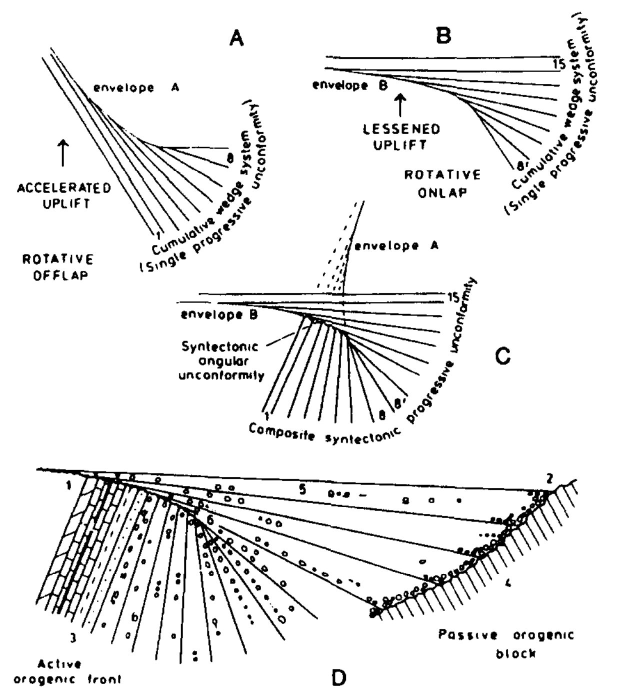

Fig. 8. Genetic model of syntectonic unconformity (c & d), resulting from a combination of rotative offlap (a) and subsequent rotative onlap (b) (after Riba 1976b).

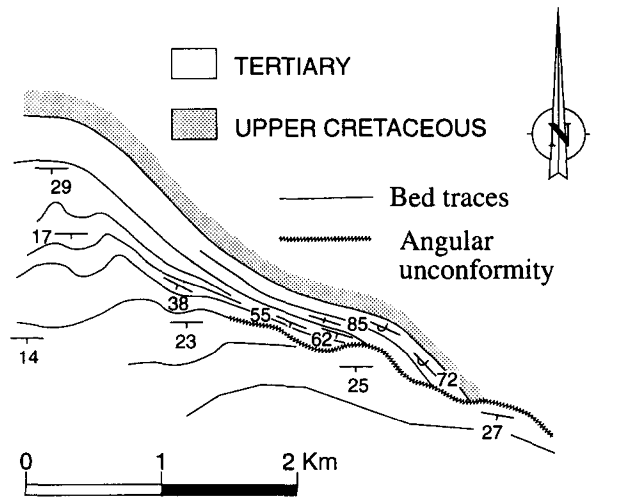

Fig. 9. Detailed geological map of the syntectonic unconformity developed in the southern limb of the Barrio anticline. Location in Fig. 2.

mity is below level 5 due to onlapping over the paleorelief (Figs. 5 and 10). The rotation of both limbs occurred simultaneously before horizon 4 was laid down, although it was greater at the southern limb (70°) than at the northern limb (35°). After horizon 6 was deposited, the southern limb rotated by 30° and the northern limb by 12°.

The third syntectonic unconformity is related to the Santibañez anticline (D in Fig. 2 and Fig. 5). In this case, rotation took place after horizon 6 had been laid down. Hence, the southern limb rotated by 45° before level 7 had been deposited, 25° between the deposit of level 7 and the base of level 8, and 15° before the Cantoral Formation (horizon 9) was deposited.

Table 1 summarizes the structural development of the study area, indicating when each fold was active. The values of limb rotation and thickness of syn-growth sediments (amplification) recorded in the table and in the text are maximum values, since limb dips decrease towards the fold terminations.

As regards the geometry of the synorogenic succession, the argument in favour of buckling is supported by the synchronous rotation of both fold limbs that differs from the syntectonic sedimentation patterns of the fault-related folds (Suppe *et al.* 1992).

Table 1. Maximum limb rotation angles and thickness of syntectonic sediments during the growth of folds in the Ubierna Fold Belt. Continuous line: fold growth period recorded by progressive unconformities. Dashed line: inaccurate fold growth period

Time (Isochrones)	LIMB ROTATION (in degrees)						AMPLIFICATION	
	Barrio Anticline		Villaescusa-Colmenares Anticlines		Santibañez Anticline		(Syntectonic sedimentary thickness in meters)	
	NL	SL	NL	SL	NL	SL		
0								
1	35	80					450	
2								Buttress deformation
3								
4	?	6	35	70			500	
5								Ubierna Fault activity ?
6							600	
7						45		Buttress deformation
8						25		
9	20	27	12	30	35	15	650	

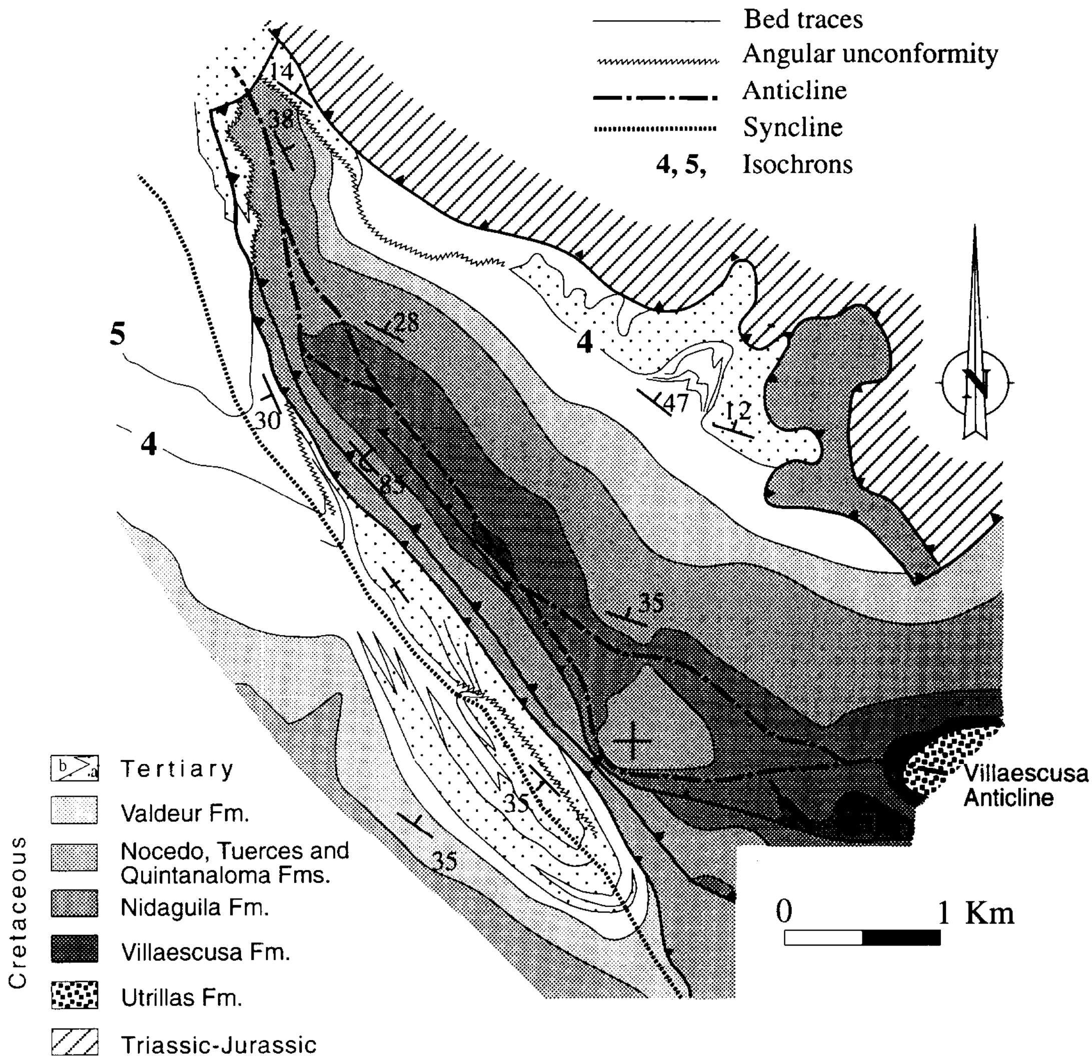

Fig. 10. Geological map of the Villaescusa anticline showing the outcrop pattern of fold-related syntectonic unconformity.

FOLD PROPAGATION: DISCUSSION

Although there is a large amount of information on natural and experimental buckling folds, references to their propagation patterns are not frequent (Biot *et al.* 1961, Erzhanoz & Egorov 1970, Cobbold 1975, Lewis & Williams 1978). These authors conclude that for a single layer, buckling folds propagate serially along the layering by the successive addition of new folds from an initial site of perturbation and producing a direct relationship between the amplitude and the time that had elapsed since their formation. Model experiments for multilayers (Watkinson 1976) lead to similar conclusions: an initial fold leads to the development of new folds on both sides.

The progressive development of the Ubierna Fold Belt is shown in Fig. 11. The fold propagation pattern is deduced from the relative age of the syntectonic unconformities (Table 1): it began in the north (folding started with the development of the Barrio anticline during the 0–1 interval (Fig. 11,IIB) and a weaker rotation took place during the 3–4 interval) and propagated southwards (the Villaescusa and Colmenares anticlines grew at least during the 1–4 interval; Fig. 11,IIIB). Later on, during the 6–9 interval, the Santibañez anticline developed (Fig. 11,IIC and IIIC). The fact that maximum amplitude decays southwards in some of the cross-sections (Fig. 5) also suggests that folds propagated in that direction.

Besides the propagation sequence described above, there is a late episode (post-isochron 6) during which the earlier folds were tightened synchronously with the development of the southernmost fold (Fig. 5). This latest stage consists of a combination of fold amplification and tilting of the fold train envelope surfaces.

The amplification periods of the two earlier folds (Table 1) overlapped scantily in contrast with the results from some experimental works (Biot *et al.* 1961, Cobbold 1975). Propagation was essentially sequential, that is, a fold begins to amplify when the previous one locks up, probably because, as Lewis & Williams (1978) suggest, if the initial perturbation has a high amplitude it will be weak and will absorb the compression. When the primary fold locks, the strain at the front may increase adding a new fold to the flank of the fold already formed.

An explanation must be found to the second tightening or synchronous amplification episode of every fold in isochrone 6. It could be related to the tilting of the

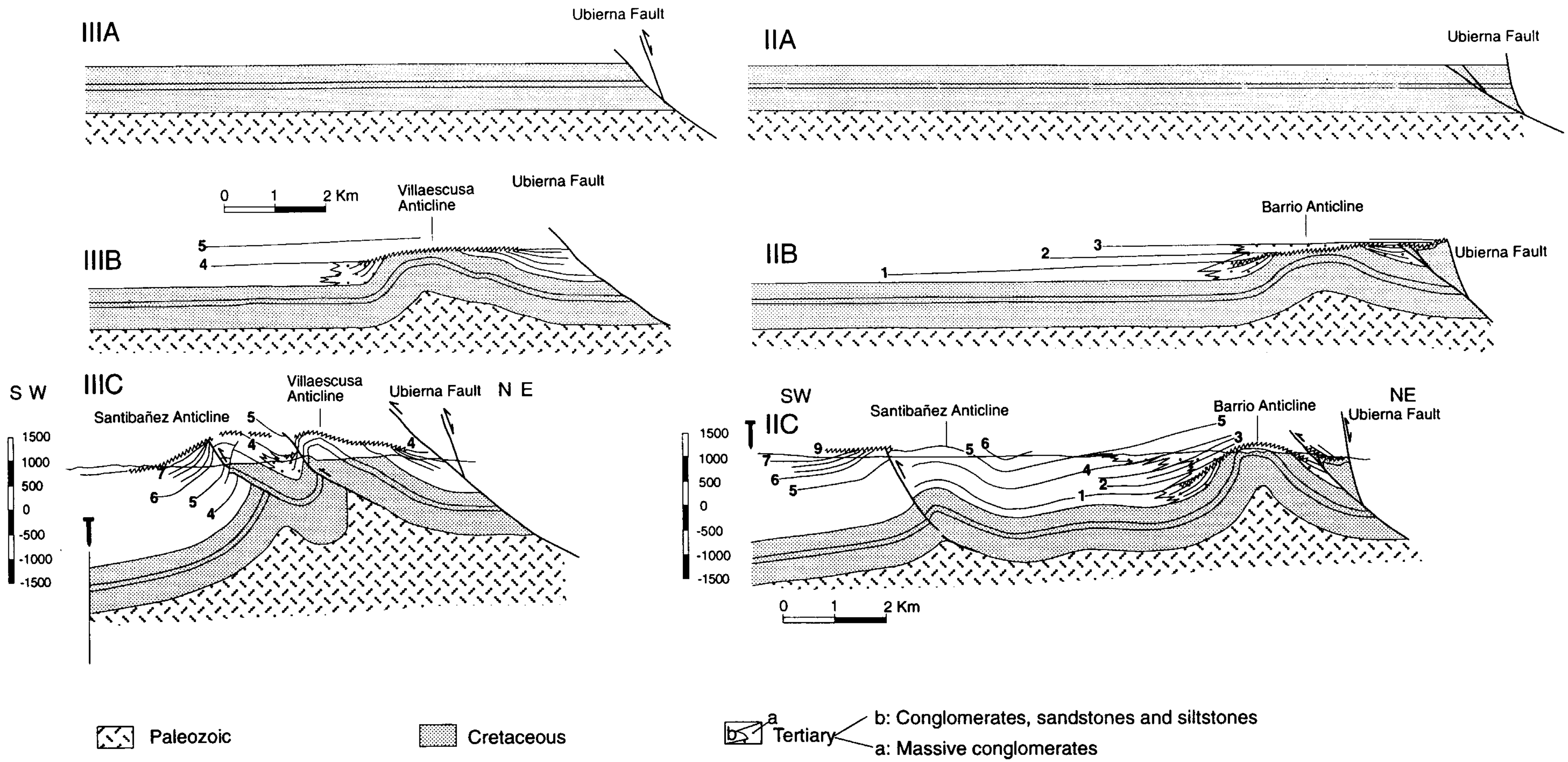

Fig. 11. Sequence diagram showing the progressive development of the Ubierna Fold Belt. Right: progressive development of the folds in cross-section II. Left: progressive development of the folds in cross-section III.

envelope surface of the folds train occurring at that time. This tilting must have orientated the enveloping surface more perpendicularly to the *XY* deformation plane, which would have encouraged fold amplification, as stated in the experimental work on inclined layers buckling (Anthony & Wickham 1978).

In the 0–1 interval no growth fold occurred in cross-section III (Table 1 and Fig. 11, IIIB). This difference in the initiation of Barrio and Villaescusa folds can be related to the geometry of the Ubierna fault in this area, where it shows a prominent trend change from NW–SE to NE–SW (Fig. 2). This can be interpreted as a lateral structure in the primitive Ubierna normal fault. During its tectonic inversion this fault segment probably also played as a lateral structure. So, the shortening that gave rise to the Barrio anticline could have been accommodated by hangingwall shortening or fault movement in the Southeastern part of the aforementioned lateral structure.

During the 4–6 interval no growth folds occurred (Table 1). A plausible explanation can be that the regional shortening was accommodated by reverse movement of the Ubierna Fault at that time.

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