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# Integration of surface and subsurface data, paleomagnetism and analogue modelling to reconstruct the extensional geometry of the Cameros basin (N Spain)

R. SOTO[1*], A. M. CASAS[2], J. J. VILLALAÍN[3], A. GIL-IMAZ[2], P. DEL RÍO[4] AND G. FERNÁNDEZ[3]

[1]*Instituto Ciencias de la Tierra Jaume Almera, CSIC, Barcelona, Spain.*

[2]*Dpto. Ciencias de la Tierra, Universidad de Zaragoza, Zaragoza, Spain.*

[3]*Dpto. Física, Universidad de Burgos, Burgos, Spain.*

[4]*Dpto. Geología, Universidad de Cadiz, Cadiz, Spain.*

[*]*e-mail: rsoto@ija.csic.es*

**Abstract:** The integration of surface, subsurface and paleomagnetic data allows the 3D reconstruction of the geometry of the northern border of the Cameros basin for its extensional, pre-inverted stage. In the model proposed, the Cameros basin represents a lens-shaped, large-scale growth syncline over a major basement fault with maximum thickness of deposits of about 8000 m in its depocenter, gradually diminishing toward the north and south. A series of analogue models validate this geometry, pointing to the role of interlayered detachment levels on the development of syncline-basin geometries.

**Keywords:** growth syncline, Cameros basin, analogue modelling, paleomagnetism, extensional geometry.

The Cameros Massif, in the northwesternmost part of the Iberian Chain, is an extensional basin formed during the Late Jurassic-Early Cretaceous and later inverted during the Tertiary (Salas and Casas, 1993). Due to this subsequent inversion, its extensional geometry must be determined from indirect data. In this work, we combine the following methodologies to reconstruct the extensional geometry of the northern border of the Cameros basin: (i) stratigraphic relationships between sedimentary units from field and photogeological studies, (ii) subsurface data (analysis of seismic reflection profiles), and (iii) paleomagnetic data following the methodology used by Villalaín *et al.* (2003) and Soto *et al.* (2008). To validate the geometric model proposed, we designed a series of analogue models simulating the characteristics of the Cameros basin.

## Geological setting

The Cameros Massif (Fig. 1) results from the inversion of the extensional Mesozoic Cameros basin. The Mesozoic sequence begins with the Lower Triassic sandstones (Buntsandstein facies), Middle Triassic limestones and dolostones (Muschelkalk facies) and Upper Triassic clays and gypsum (Keuper facies). The last-mentioned constitutes the main detachment level both during the extensional and compressional stages. Located over this detachment level, the marine Jurassic represents the pre-rift sequence. The syn-rift sequence consists of up to 8000 m of continental rocks deposited between the Oxfordian-Kimmeridgian and the Cenomanian (Muñoz *et al.*, 1997).

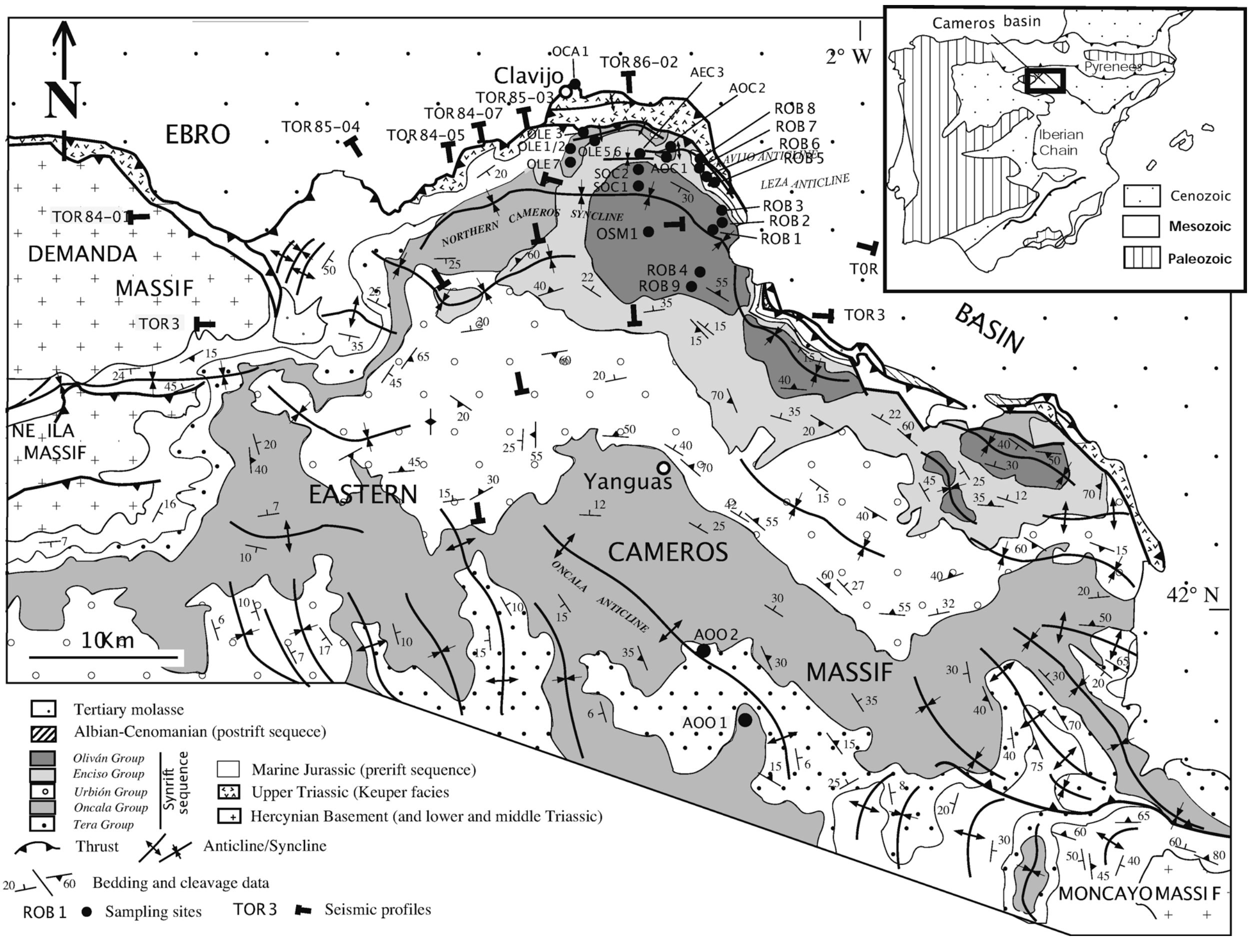


**Figure 1.** Geological map of the northern border of the Cameros Massif.

Tertiary (Eocene to Miocene) compression inverted the extensional basins, partly re-using the ancient normal faults as inverse faults (Casas *et al.*, 2000). The present-day major structure of the Cameros Massif consists of a shallow-dipping, northerly-transported thrust detached over the Upper Triassic clays and evaporites located on its northern margin (Tischer, 1966) (Fig. 1). The main syncline (northern Cameros syncline) is located near the northern border of the massif and is followed to the south by the Oncala anticline, a very gentle fold of probable extensional origin. In an overall view, a gradual thinning of the Mesozoic sequence, gently folded, can be observed from south to north.

## 3D reconstruction from surface, subsurface and paleomagnetic data

Taking into account field data, information from seismic reflection profiles and paleomagnetic data, we reconstructed the 3D extensional geometry of the northern border of the Cameros basin. Field and cartographic data help to verify the data obtained from the seismic profiles, and together pointed to thickness variations of the syn-rift sequence. Dips of beds at the extensional stage were unravelled using paleomagnetic data (see Villalaín *et al.*, 2003).

### *Surface and subsurface data*

The 3D geometry of the stratigraphic units of the northern border of the Cameros basin was reconstructed using field data and the interpretation of eight seismic profiles (five N-S and three E-W) (see location in figure 1). From these data it can be inferred that the marine Jurassic unit cannot continue to the northern basin border, and probably disappears below the core of the northern Cameros syncline. Five isopach maps were done for the five syn-rift lithostratigraphic groups described (Tera, Oncala, Urbión, Enciso and Oliván groups; Tischer, 1966) (Fig. 2). In general, the syn-rift sequence and particularly the youngest three syn-rift units show a gradual southward thickening and also

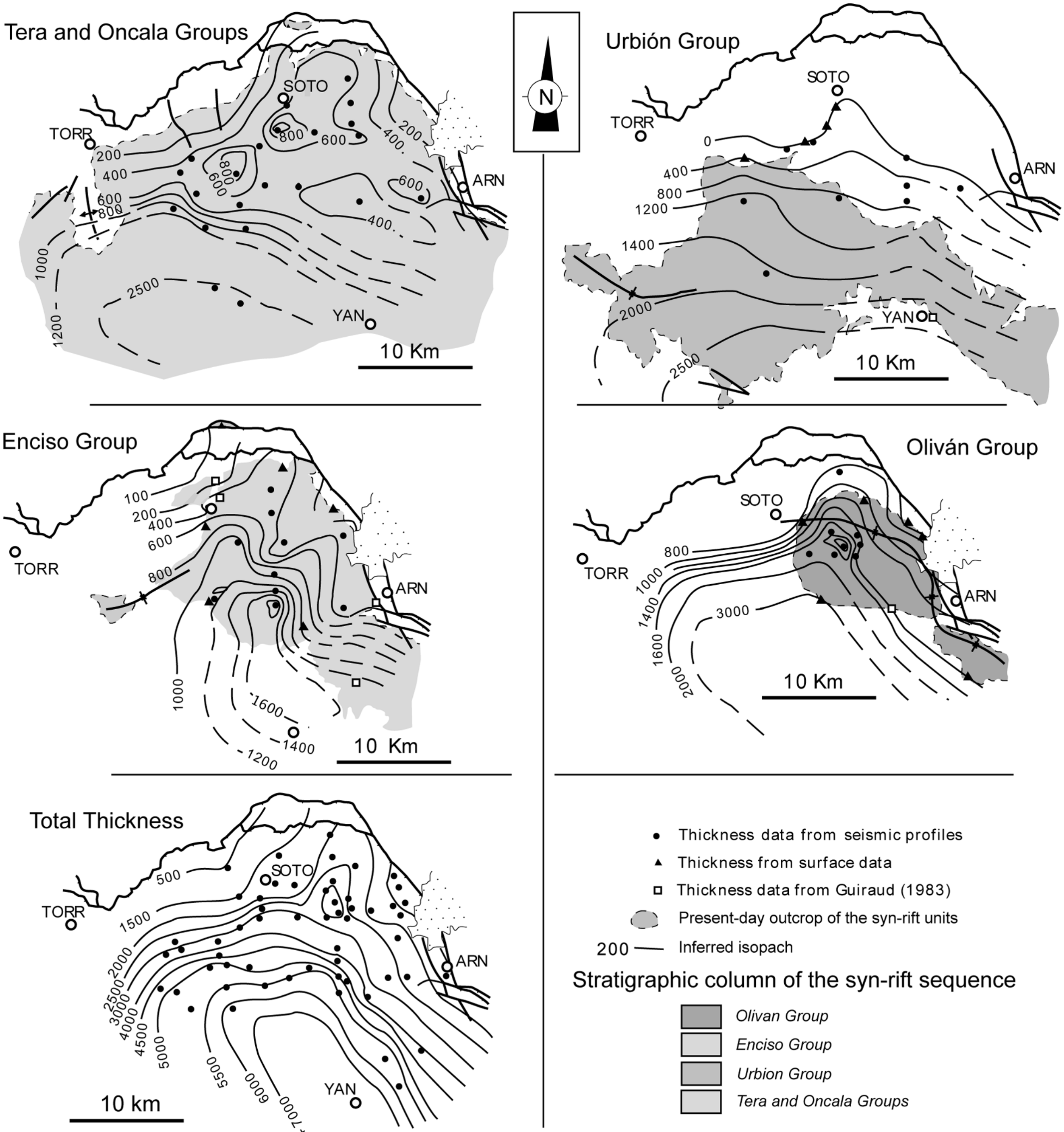


**Figure 2.** Isopach maps of the syn-rift sequences from field data and analysis of seismic profiles.

thicken from east to west (Fig. 2). This pattern is slightly modified near the northeastern basin border, where the oldest two units (Tera and Oncala groups) thicken near the northeastern normal fault limiting the basin. The isopachs allow us to characterise the present-day limits of the Cameros basin: the southeastern basin border can be defined from the thinning of units, but not the western border, where the present-day limits of units are of erosional origin. The thickness of some units, especially the Enciso group, seems to be also conditioned by other faults, with NNE-SSW to NE-SW strike, oblique or perpendicular to the main structural trend (Fig. 2).

## *Paleomagnetic data*

Paleomagnetism constitutes a useful technique to reconstruct the geometry of inverted sedimentary

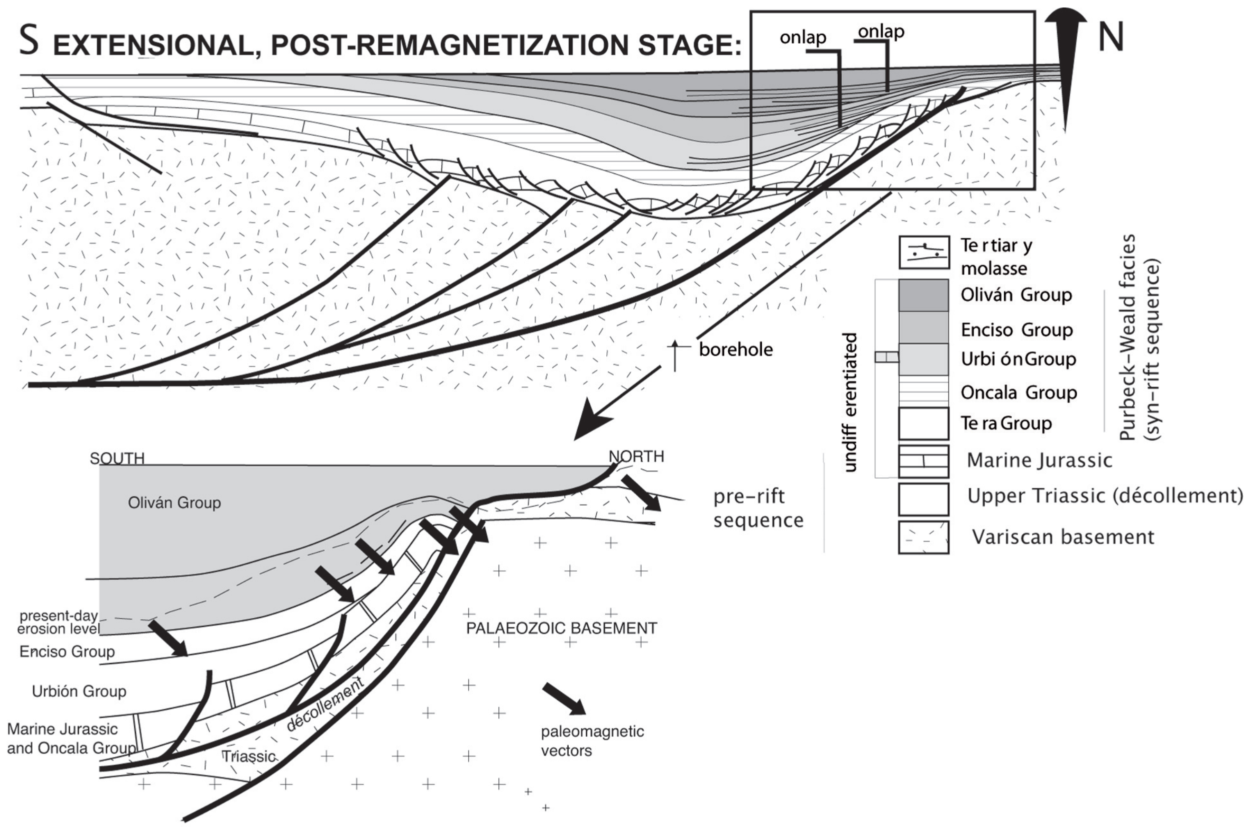


**Figure 3.** Reconstruction of the extensional geometry of the northern border of the Cameros basin from paleomagnetic data (see Villalaín *et al.* (2003) for more details).

basins when a post-extensional, pre-inversion magnetic overprint (i.e. syntectonic remagnetization) has been recorded by the sediments (Villalaín *et al.*, 2003; Soto *et al.*, 2008). Twenty four sites were analysed in the syn-rift sequence and distributed along three transects (see location in figure 1), perpendicular to the present-day northern border of the Cameros Massif. The magnetic properties of the rocks are described in more detail in Villalaín *et al.* (2003). The magnetization of the samples is interpreted as having been acquired in relation to the extensional stage and before the tectonic inversion of the basin. Using the Small Circle Intersection (SCI) method (Waldhör and Appel, 2006), we calculated the expected direction of the remagnetization (Dec = 359.0º, Inc = 51.5º, $a_{95}$ = 4.2º). The applied rotation necessary to restore the magnetization to the expected direction can be applied to beds in each site, thus producing the tilting of beds at the remagnetization time (i.e. at the extensional stage) (see Soto *et al.*, 2008).

In the reconstruction obtained from paleomagnetic data for the pre-Tertiary compressional times a widespread southward dip can be observed in most of the analysed sites (Fig. 3). Near the northern basin border, the pre-inversion dip of beds also changes to horizontal or northward dip (Figs. 1 and 3). A progressive decrease in the original dips can also be observed, with very shallow original dips in sites located in the southern limb of the northern Cameros syncline (Figs. 1 and 3).

### *3D reconstruction of the extensional geometry of the Cameros basin*

The most significant extensional structure preserved in the northern border of the Cameros basin is the E-W-trending anticline, interpreted as a roll-over anticline, that runs along one of the faults which marked the probable northern basin border (Leza anticline) (Fig. 3). From paleomagnetic data a compressional tightening of this anticline, together with the formation of minor folds after the remagnetization, can be inferred (Fig. 3). The syn-rift sequence thickens progressively from the northern border to the central part of the Cameros basin. This feature together with the paleomagnetic results indicate that the overall geometry of the basin is a growth syncline, with a master normal fault limiting the basin to the north (Fig. 3). No large-scale "reverse" drag (roll-over anticline) can be inferred from thickness data. The roll-over inferred from palaeomagnetic data (i.e. tightened Leza anticline) is restricted to the area close to the basin margin and does not modify significantly the geometry of the sedimentary wedge.

## Validation of the model with analogue experiments

In order to validate the geometry inferred for the Cameros basin, we performed a series of analogue models simulating its pre-rift and syn-rift deposits (Soto *et al.*, 2007). Pre-rift layers of sand (100-300 μm in size and ϕ = 33.5º internal friction angle) were sieved and arranged into horizontal sequences 125 mm-thick. To simulate the behaviour of the Upper Triassic clays and gypsum (Keuper facies), a 10 mm-thick silicone (Rhodorsil Gomme FB of Rhodia silicones) layer (with the properties of an almost Newtonian fluid) was placed in the upper part of the pre-rift sediments. The experiments were carried out in a sand-box with a rigid and fixed listric-shaped footwall block dipping 60º at surface with a constant displacement rate of 15 mm $h^{-1}$ (Fig. 4). The syn-rift sequence was added after every 15 mm of displacement. Also, a reference model without interlayered viscous décollement (Fig. 4B) was prepared to compare with brittle-ductile models (Fig. 4C).

In all experiments, the geometry of the pre-rift sequence (i.e. the equivalent to the Paleozoic basement in the Cameros basin) described a roll-over anticline (Figs. 4B and 4C). This roll-over anticline and associated synchronous crestal-collapse faults constituted the only structures in the model without viscous layer (Fig. 4B). By way of contrast, experiment with interlayered décollement shows a growth syncline geometry with upward-decreasing dip values of the syn-rift deposits and a secondary, very gentle and narrow roll-over anticline, also with upward-decreasing dip values and formed against the boundary-major fault (Fig. 4C). These two features constitute the geometry interpreted for the Cameros basin from surface, subsurface and paleomagnetic data. Basinward dips of the syn-rift sequence in the Cameros basin (Villalaín *et al.*, 2003) indicate a syn-sedimentary syncline geometry as in the experiment of figure 4C. Secondary structures described at the northern border of the Cameros basin, as roll-over anticlines (Leza anticline; Villalaín *et al.*, 2003), also fit in with some

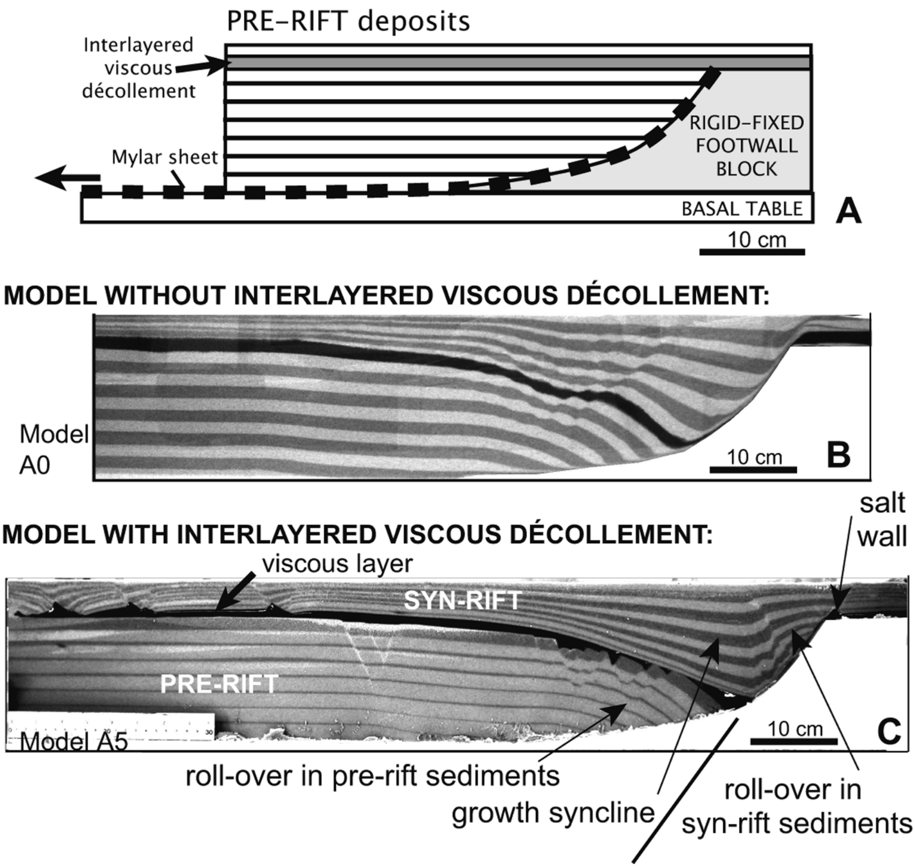


**Figure 4.** (A) Experimental apparatus, (B) cross-section photograph of model without interlayered viscous décollement, (C) cross-section photograph of model with interlayered viscous décollement. Note the similarities between model with interlayered viscous décollement and the basinal cross-section of figure 3 regarding their large-scale growth syncline geometry and secondary syn-rift roll-over anticlines close to the master fault.

of the features described in the model with an interlayered décollement. Also, the large outcrops of Upper Triassic clays and gypsum (Keuper facies) coinciding with the Cameros thrust front (Fig. 1) fit well with the formation of salt walls on the footwall cutoff of the listric fault that the experiment shows.

## Conclusions

The comparison between the experiments and the geometry of the northern margin of the Cameros basin inferred from surface, subsurface and paleomagnetic data supports: (1) the major role played by the presence of a viscous layer in the pre-rift deposits on the sedimentary architecture of the syn-rift deposits, (2) the gentle increase in thickness of the syn-rift sequence toward the core of the syn-sedimentary syncline, as is also shown by the isopachs of the sedimentary units, and (3) the "syn-sedimentary" changes in dip of the syn-rift sequence close to the major fault limiting the basin, evidenced by the paleomagnetic study.

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