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3D kinematics of the Sant Corneli anticline: insights from structural reconstruction and forward modelling

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Abstract: The work presented here consists in the 3D structural reconstruction and forward modelling of a fault-related structure, the Sant Corneli anticline in the southern Pyrenees, from field and subsurface data. The process involves several steps: 3D digitalization, structural and stratigraphic analysis, surface construction, and numerical modelling. Each one of them can be adapted to the different nature of the surfaces under construction and to the origin of the data sets. 3D reconstruction is constrained and/or completed by using a forward modelling technique for data extrapolation. Moreover, different kinematic hypotheses can be tested. This three-dimensional approach permits a better understanding of areas with structural and stratigraphic complexities.

Keywords: 3D reconstruction, fault-related folding, forward modelling, 3D mapping, 3D kinematics.

Much of the work concerning the characterization of fold and thrust structures and the relationship between them has classically focused on the search for, and definition of, 2D geometric and kinematic models, usually parallel to the thrust transport direction (Suppe and Medwedeff, 1990; Mitra, 2002). Recently, the development of new techniques for data acquisition, management, analysis, modelling and visualization has opened up the possibility to analyse and describe geological structures in 3D.

The work presented here consists in the 3D structural reconstruction and forward modelling of a fault-related fold, the Sant Corneli anticline in the southern Pyrenees (Fig. 1). The cornerstone of this methodology is that it works with data in their existing coordinates, avoiding errors derived from data projection into 2D cross-sections. Cross-section construction prior to 3D modelling may obscure structural variations along-strike that can lead to misinterpretations of the structural evolution of complex geological structures.

Geological setting

The Sant Corneli anticline is located at the thrust front of the Bóixols thrust sheet (Fig. 1). This fold trends E-W and crops out for more than 50 km. The Bóixols thrust sheet is a major structural unit of the central Pyrenees, infilled by Mesozoic rocks, which resulted from the inversion in Late Cretaceous times of an earlier system of extensional basins, which were developed during Early Cretaceous (Bond and McClay, 1995; Muñoz, 2002). During the Alpine orogeny, these basins were inverted and incorporated into the Pyrenean thrust sheets (Late Santonian-Early Miocene) (Muñoz, 2002). This is the case of the Organyà basin and the subsequent Bóixols thrust sheet (Garrido-Mejías, 1973; Cámara and Klimowitz, 1985; Berástegui *et al.*, 1990; Bond and McClay, 1995; García-Senz, 2002). The Sant Corneli anticline is cored at the surface by synrift materials (Upper Aptian-Middle Albian) (Fig. 1), so that older materials do not crop out in the study area. The beds that best delineate the geometry of the fold are those correspon-

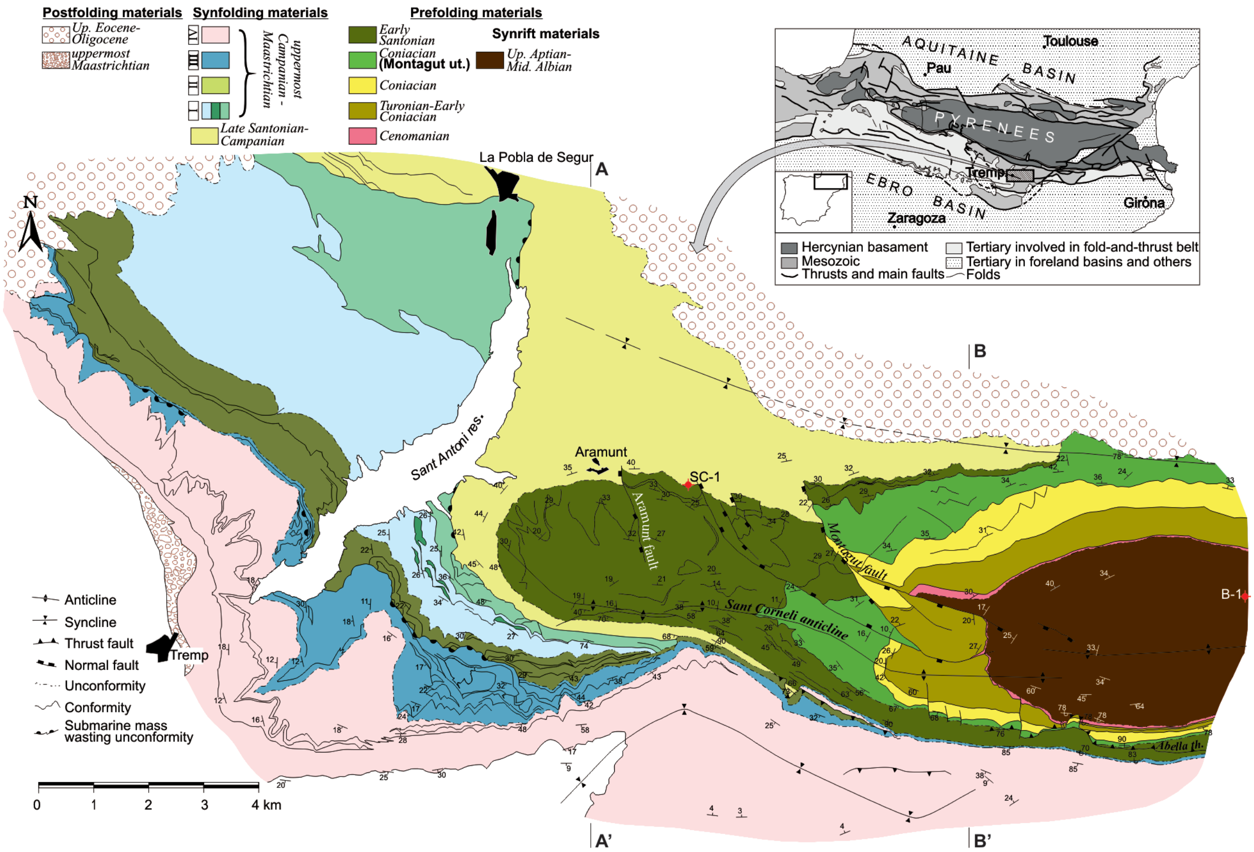

Figure 1. Geological setting of the studied area (geological map of the synfolding materials based on an unpublished work carried out by P. Arbués, N. Carrera, J. Mencos and J. A. Muñoz). A-A' and B-B' correspond to the cross-sections shown in figure 2 (obtained from the 3D model).

ding to the post-rift sequence (Cenomanian-Lower Santonian) (Fig. 1). To the western part of the study area, the fold plunge increases abruptly, causing the disappearance of the surface expression of the fold westwards. There the synfolding sediments (Upper Santonian-Maastrichtian) (Fig. 1) expand over the entire structure. Postfolding materials (Upper Eocene-Oligocene) (Fig. 1) crop out away from the structure.

Methodology

The methodology proposed in this paper aims at the reconstruction of the geological surfaces that best represent the 3D geometry of the fold, as well as the thrust surface. It employs whatever data is available, field data in this case, data derived from 3D mapping techniques and subsurface geophysical data (Mencos *et al.*, *in press*).

The process of reconstruction has been attempted following different approaches, depending on the nature, exposure and availability of information of the geological surfaces under study.

The first part of the work was the reconstruction at the surface of the prefolding strata that best delineate the geometry of the fold. Secondly, we performed the 3D model of the thrust surface to which the anticline is related (Fig. 2a). Finally, we proceeded with the reconstruction of the synfolding sequence in order to obtain a complete image of the Sant Corneli anticline and its related deposits (Fig. 2b).

Forward modelling was integrated into the 3D reconstruction workflow in order to decipher geometric relationships between the different reconstructed elements, to extrapolate data having geological sense, to analyse different parameters controlling the structure evolution (and their variation through space and time), as well as to propose a kinematic evolution for the anticline (Hardy and Poblet, 1995) (Figs. 2c and 2d).

The process of 3D reconstruction involves several steps that can be summarized as follows: 3D digitalization, structural and stratigraphic analysis, surface construction, numerical modelling (Fig. 3).

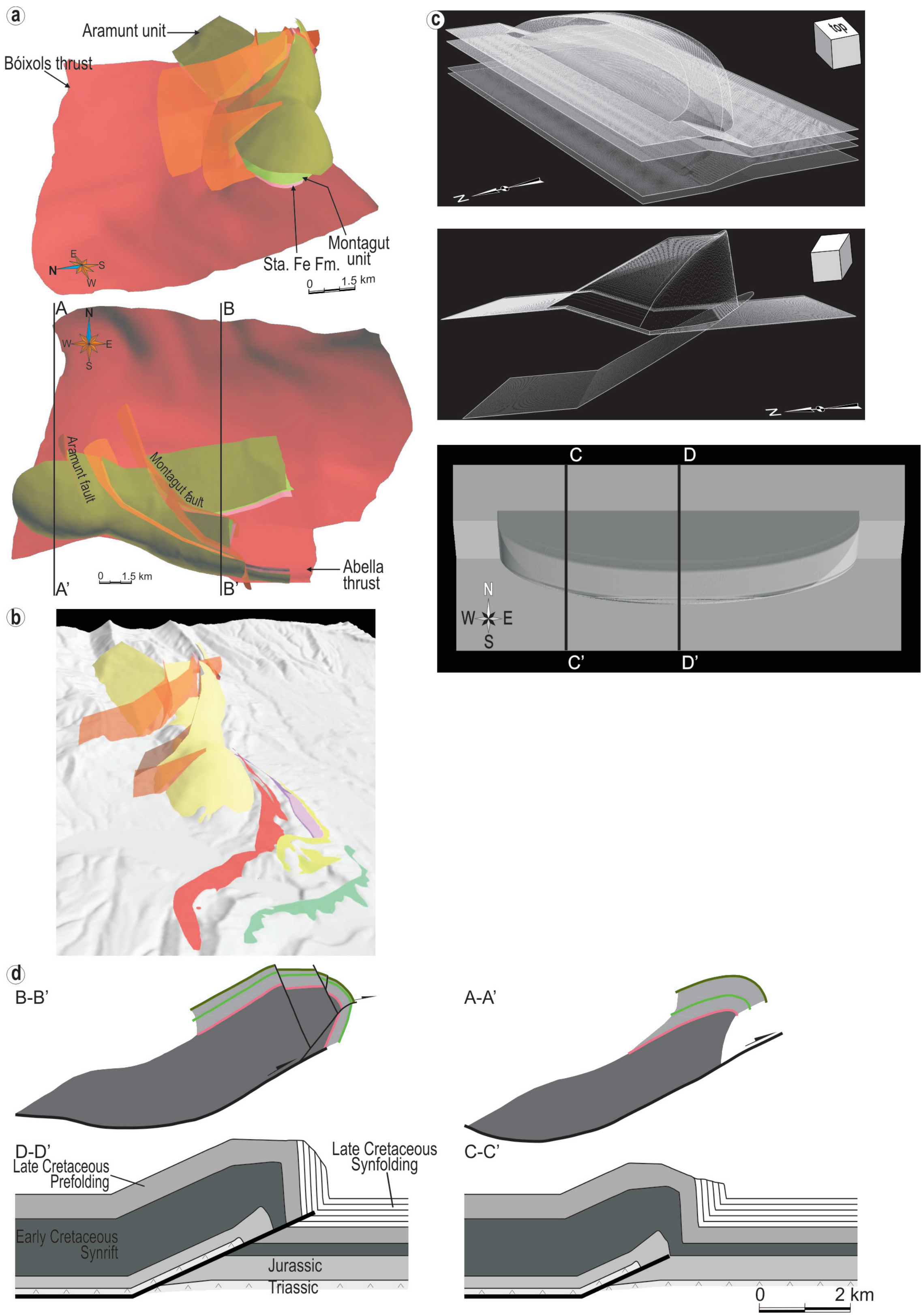

Figure 2. 3D reconstruction. a) Thrust and prefolding strata. Top: view from NW, below: top view, b) synfolding surfaces intersected with the DTM, view from NW, c) forward modelling; from top: View from NW, view from SW and top view, d) cross-sections obtained from the 3D model (top) and from the forward model (below). Horizon patterns are the same as used in figure 1.

Analysis and results

Three prefolding surfaces were reconstructed within the postrift sequence (bottom of Sta. Fe formation, Cenomanian in age; bottom of Montagut and top of Aramunt units, Coniacian-Lower Santonian in age). In addition, four oblique normal faults compartmentalizing the fold were created as well as a minor thrust affecting the frontal limb (Fig. 2). Prefolding surfaces and minor faults were reconstructed using field data and constrained by an exploration well present in the area (Fig. 1). Finally, the Bóixols thrust surface was also reconstructed from subsurface information (Fig. 2).

The 3D reconstruction reveals an asymmetric fold with along-strike geometric variations. The most remarkable ones are changes in the plunge axis that coincide mostly with the location of the oblique extensional faults. Near Sant Antoni reservoir (Fig. 1) the fold plunge experiments a sudden dip increase that results in the disappearance of the surface expression of the fold westwards.

The Bóixols thrust depicts a near horizontal flat and a frontal ramp in the study area, with a coincident dip with the fold backlimb. The bottom of the footwall ramp displays a west plunging line with a sudden plunge increase near the Sant Antoni reservoir.

In the case of the synfolding sequence, five surfaces were reconstructed, representing four different depositional events (Fig. 2). These depositional sequences are bounded by major or local unconformities and within each of them horizons display normal and transitional contacts. They represent deposition under submarine conditions near the coastline, evolving from inner-outer platform to beach conditions through time (Arbués *et al.*, 1996; Ardèvol *et al.*, 2000). In this case, the 3D model was performed using field data only.

Discussion and conclusions

Comparing the geometry of the fold and the thrust, it can be observed that while the thrust geometry at depth remains constant, the fold geometry at the surface shows along-strike variations, especially in the plunge of the fold. These along-strike variations do not correspond to variations in the thrust geometry, which is constant overall with a deepening of the thrust flat to the west.

The area which demonstrates the most significant changes in the attitude of the fold axis, and changes in the fold geometry itself, coincides with the occurrence of the oblique extensional faults which compartmentalize the fold and also with the area where the synrift deposits undergo considerable thinning (observed in seismic). This fact is crucial in explaining the longitudinal variation in the fold geometry and could be related to the position and geometry of the previous extensional basin margin. The location

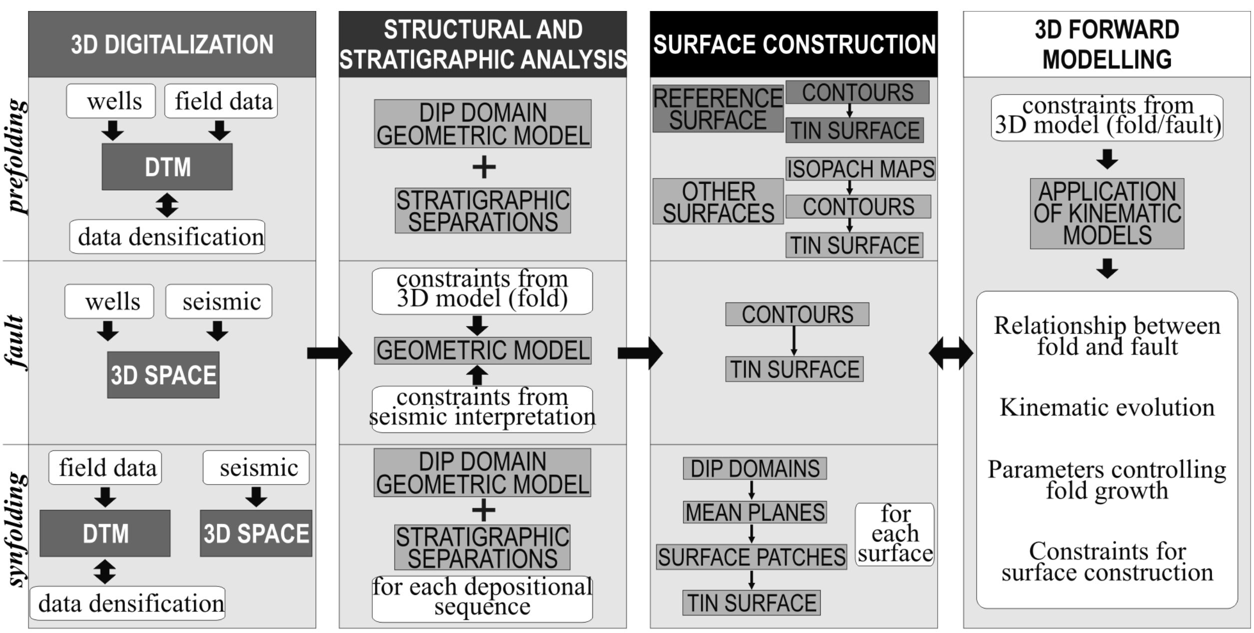

Figure 3. 3D reconstruction workflow.

and nature of these along-strike variations have not been reported before in the literature, being one of the new contributions of this work in the understanding of the structure and evolution of the Sant Corneli anticline.

Near Sant Antoni reservoir, the anticline shows an abrupt increase of the fold plunge coincident with a deepening of the thrust surface. Both the anticline and the thrust continue in the subsurface, as observed in seismic lines.

The Sant Corneli fault-related anticline was developed above the frontal ramp of a blind thrust, which occurred in the footwall of a previous extensional fault (Organyà fault). This fault crops out further to the west in the core of the anticline, close to the axial surface (Berástegui *et al.*, 1990). The upper part of the extensional fault affecting synrift sediments has only been partially reactivated. Its footwall corresponds to the forelimb of the anticline, which on the other hand represents a short-cut in the hangingwall of the Bóixols thrust.

The Bóixols thrust is detached into the Keuper evaporites which at present are at the same structural elevation both in the hangingwall and in the footwall of the thrust. As a consequence, the bottom of the postrift is structurally higher in the hangingwall as it involves a significantly thicker succession of synrift sediments. The thickness of this succession, up to 4 km thicker in the hangingwall than in the footwall and the geometry of the extensional fault, suggest that the basement was involved during extensional faulting. However, it is not involved in the Sant Corneli anticline. To account for this structural configuration, an initial stage of inversion has been proposed, reactivating the basement-involved extensional fault, followed by the detachment of the Mesozoic cover above the Triassic evaporites (Muñoz, 2002).

To reproduce such inferred evolution, the numerical modelling has been designed considering an initial structural elevation difference for the top of the synrift sediments, together with a dramatic thickness change in the transition zone between the hangingwall and the footwall of the future Bóixols thrust, representing initial inversion of the extensional fault previously to thrust development. This initial configuration has been designed as the applied modelling technique cannot deal with inversion of previous modelled extensional features. Without this assumption regarding the initial configuration, the present-day geometry cannot be satisfactorily reproduced. After applying several fault-fold deformation models, we can conclude that the numerical modelling performed suggests that fault-propagation fold models with constant bed thickness (Suppe and Medwedeff, 1990) best account for most of the features of the folded postrift sequence (Fig. 2). However, it does not efficiently fit in with the geometries displayed by the synfolding materials.

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