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Structural analysis and deformation architecture of a fault-propagation fold in the southern Cantabrian Mountains, NW Iberian Peninsula

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Abstract: Fault-propagation folds are important contractional structures developed in upper crustal conditions. Here we analyze a fault-propagation fold, made up of Carboniferous limestones, sited in the Cantabrian fold and thrust belt, NW Iberian Peninsula. The technique employed consists of detailed structural analysis integrated with cross-section restoration. Such approach allowed us to validate the geological interpretation and to decipher the deformation architecture using an inverse model based on strain markers. The results are illustrated overlapping contour maps and diagrams on top of the deformed, present-day cross section.

Keywords: fault-propagation fold, Cantabrian Zone, displacement vs. distance graph, cross-section restoration, deformation architecture.

Fault-propagation folds related to thrusts accommodate shortening in upper crustal levels and are common tectonic structures developed in several contractional settings such as fold and thrust belts, accretionary prisms, frontal part of prograding deltas, etc. (e.g. Mitra, 1990; Suppe and Medwedeff, 1990). The scientific literature describes copiously fault-propagation folds, but a large number of articles deal with theoretical models of this type of folds and much less natural examples have been studied in detail (e.g. Jamison, 1987; Mitra, 1990; Suppe and Medwedeff, 1990).

Here we carried out a detailed study of an outcrop-scale fault-propagation fold located in the Cantabrian Mountains, NW Iberian Peninsula. The structural analysis involved field measurements and observations about the nature and the spatial orientation of the structural elements, such as faults, folds and kinematic indicators, and of bedding. After that, the fold was interpreted using a photograph and a sub-surface portion of the structure was extrapolated from the available surface data. Moreover, a diagram of distance along the fault zone vs. displacement was constructed in order to decipher the nature of the structure. Cross-section restoration was employed to validate the geological interpretation as well as to calculate the shortening. Furthermore, the deformation was simulated using a technique based on including strain markers in the cross section subsequently restored (Masini *et al.*, *submitted*).

The fold analyzed here was chosen due to its excellent exposure, well-known stratigraphy as well as the accessibility that permitted the construction of an accurate cross section.

Geological setting

The Cantabrian zone is the external part of the Variscan orogen in NW Iberian Peninsula. The

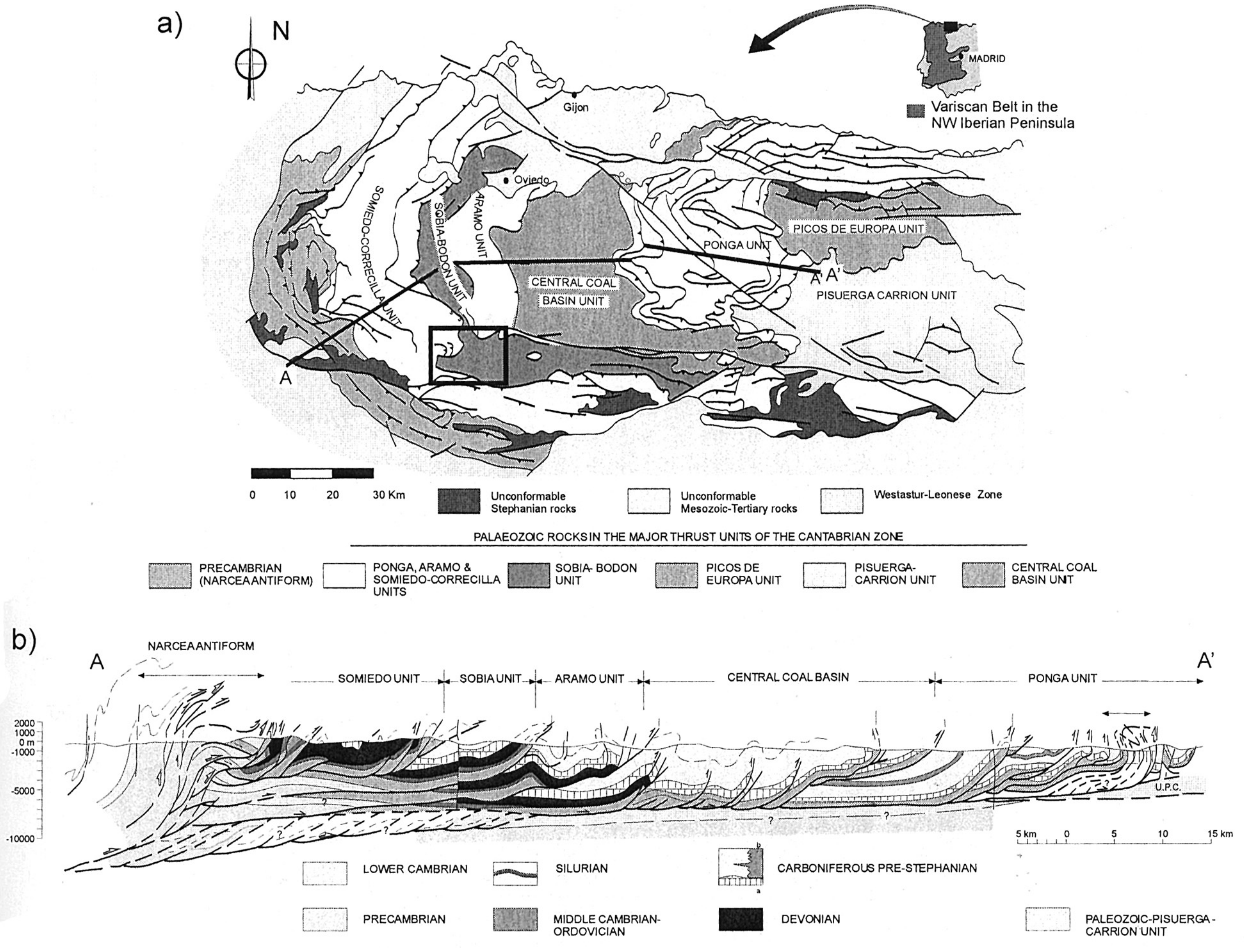

Figure 1. (a) Structural map of the Cantabrian zone (NW Iberian Peninsula). The studied area is located within the box (west termination of the Bodón structural unit), (b) section A-A' across the Cantabrian fold and thrust belt (modified from Pérez-Estaún *et al.*, 1988).

Cantabrian fold and thrust belt shows an arcuate geometry in map view known as Ibero-Armorican Arc or Asturian Arc (Fig. 1a). A section across the Cantabrian zone (Fig. 1b) shows an imbricate thrust system with a wedge shape progressively thinner toward the east and where the structures involve almost the entire Palaeozoic sedimentary succession, from Cambrian to Carboniferous (Julivert, 1981; Savage, 1981; Pérez-Estaún *et al.*, 1988; Pérez-Estaún and Bastida, 1990; Aller *et al.*, 2004).

The structure presented here is named Los Fuejos in relationship to a local toponym and it is sited in the north limb of the Villasecino anticline that consists of an upright, regional-scale anticline with an approximately E-W striking axial plane. Such regional structure, probably developed during Variscan times, is located in the Huergas semi-tectonic window, at the western termination of the Bodón structural unit (De Sitter, 1962; Marcos, 1968; Martínez-Álvarez *et al.*, 1968; Alonso *et al.*, 1989; Suárez-Rodríguez *et al.*, 1990).

Main structural features

Los Fuejos structure, exposed along a NNE-SSW portion of a local road (Fig. 2a), involves well-bedded red, nodular limestones and radiolarites (Alba Fm, Carboniferous), and light coloured limestones and black shales (Baleas and Vegamián Fms respectively, Upper Devonian and Carboniferous) (Fig. 2b). Here we analyse only the red, nodular limestones, because the radiolarites are detached from the underlying limestones and the shortening is accommodated through smaller-scale folding (Fig. 2a).

The main structure consists of a major fold and an imbricate fault system. The fold axial surface dips steeply to the SSW and the fold axes are subhorizontal and ESE-WNW trending (Fig. 2d). Fault surfaces

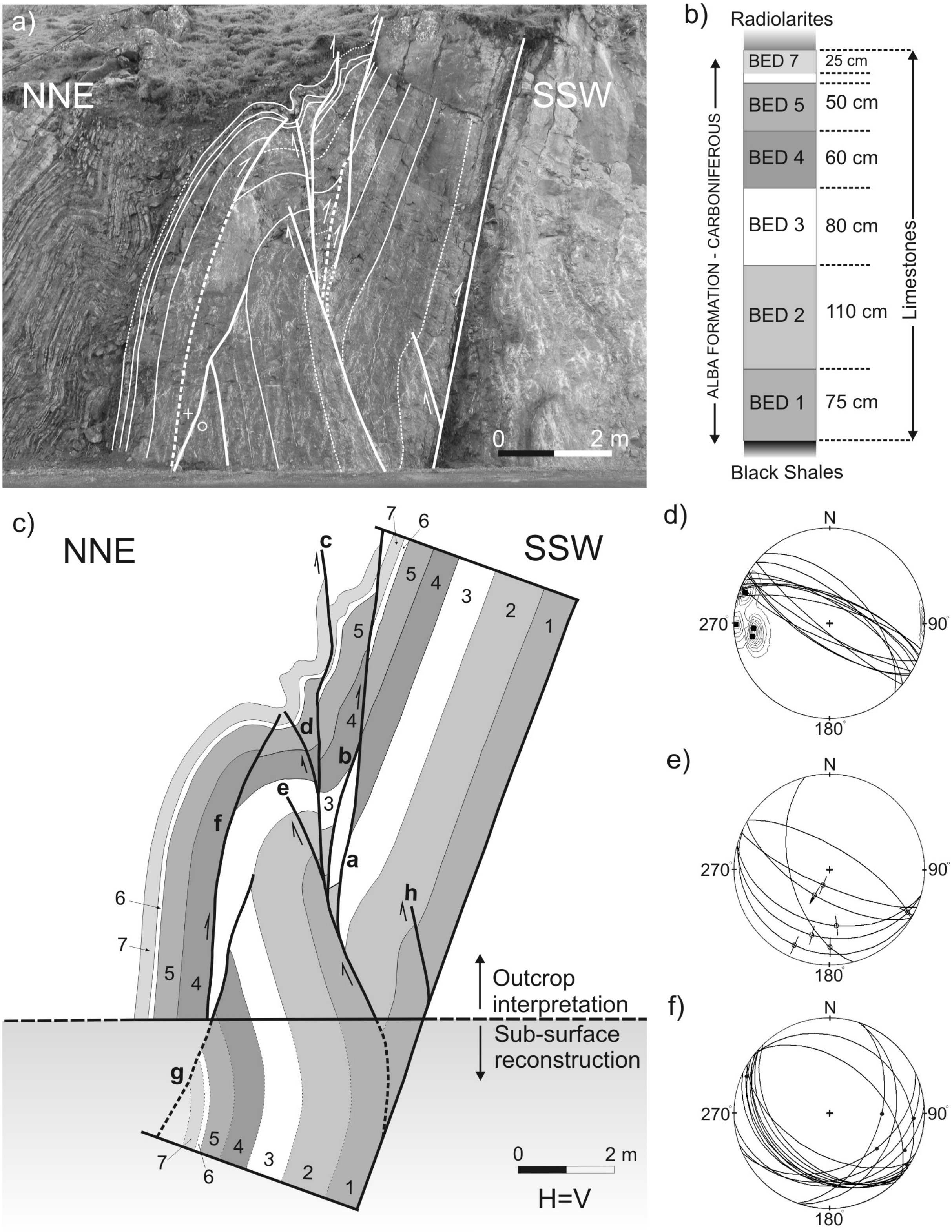

Figure 2. (a) Interpreted photograph of Los Fuejos structure, (b) stratigraphic column of the sedimentary sequence (limestones) involved in the structure, (c) deformed, present-day section across Los Fuejos structure. The subsurface portion was completed assuming that the thrust displays a hangingwall flat over a footwall ramp and branches with a detachment; (d, e and f) Schmidt projections of the main structural elements: (d) bedding and fold axes, (e) faults, (f) cleavage and intersections between cleavage and bedding.

dip steeply to both SSW and NNE (Fig. 2e). The structure is affected by a cleavage mainly dipping to the SSW and NNE (Fig. 2f). The actual disposition of both beds and structures results in an apparent normal movement along some faults and a reverse displacement along others.

Construction of a geological profile

In order to visualize accurately the geometry of the structure, a grid was constructed in the field; knowing the distances between different grid nodes and the spatial orientation of the structural elements, the distortions due to photograph perspective were corrected (Figs. 2a and c). The geological cross-section was not correct yet because the outcrop orientation is not perpendicular to the fold axes. For this reason it was necessary to apply a technique described by Ramsay and Huber (1987) to obtain a geological profile approximately perpendicular to the fold axis and parallel to the tectonic transport vector using a mean fold axis that dips 7° toward direction 290° (Fig. 2c). During the last operation, the fault *g* in figure 2c, apparently a backthrust, but with strike slip kinematic indicators, was removed and such portion of the cross section was redrawn accordingly. This structure was removed because it implies out-of-plane movement which cannot be properly restored. Furthermore, the entire profile was rotated in order to obtain the tilted bedding of the SSW part of the cross section in horizontal position, using a rotation axis that corresponds to the approximate axis of the regional-scale Villasecino anticline (Fig. 3a).

Fault-fold relationships

Following the procedure described in the previous section, we achieved the cross section displayed in figure 3a, that shows a major asymmetrical anticline with a gentle north limb and a steeper south limb. The syncline located to the south of the anticline exhibits minor folds and a thrust system that merges into a basal detachment sited at a black shale level (Figs. 2a and c).

The kinematic indicators (striations and slickensides on the fault surfaces, vergence of minor folds, etc.) point out a tectonic transport vector toward the SSW consistent with the vergence of the major fold.

The sub-surface portion of the structure was completed using the "projecting faults to depth" technique (Roeder *et al.*, 1978), assuming that the main thrust displays a hangingwall flat over a footwall ramp and branches with a well-known local detachment at the boundary between the Alba and the Baleas Fms within the Vegamián Fm (this detachment is observed in the outcrop displayed in figure 2a).

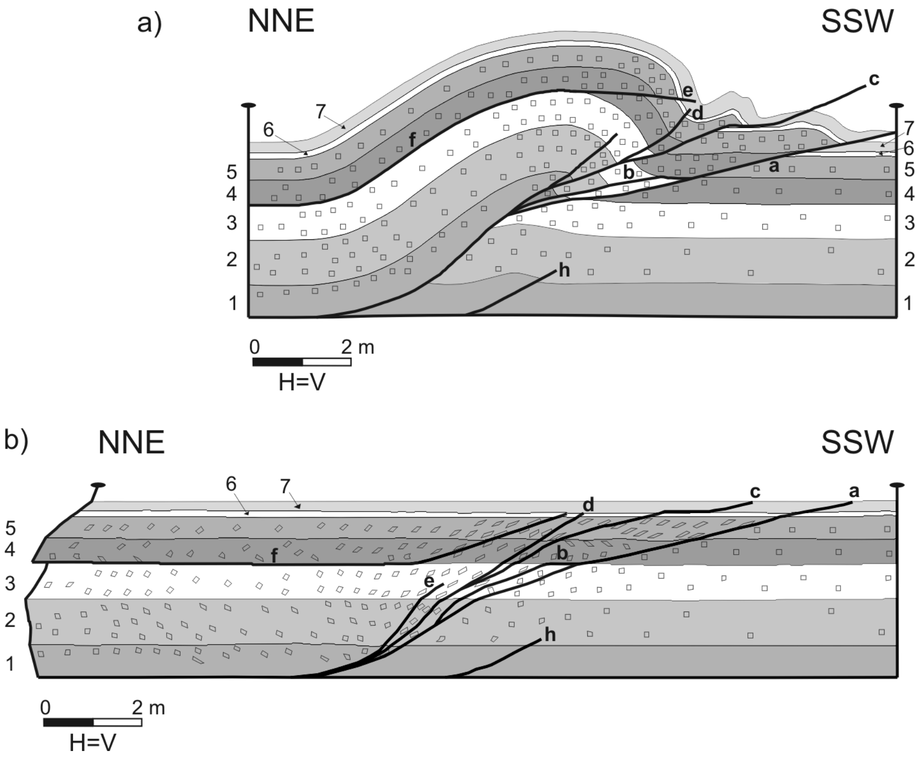

Figure 3. (a) Balanced section across Los Fuejos Structure, (b) restoration of the deformed, present-day cross section using the layer-parallel shear algorithm (and equal-area restoration where local thickness variation occur). In both sections, undeformed and deformed strain markers used to simulate the deformation are displayed.

The detailed interpretation of the displacement vs. distance along a fault function is difficult because it depends on the rheology of the rocks (e.g. Muraoka and Kamata, 1983), type of fold (McConnell *et al.*, 1997) and cut-off angles, however, the displacement vs. distance along fault *a* (see figure 2c) graph displayed in figure 4 suggests that fault displacement progressively decreases stratigraphycally upwards and may be transferred into folding and other faults.

The fold asymmetry, the steep dip of the anticline forelimb, the occurrence of a syncline located in the frontal part of the anticline where many thrusts die and the loss of fault displacement accommodated by folding stratigraphycally upwards allows us to interpret Los Fuejos structure as a fault-propagation fold. This interpretation is in accordance with other structures documented in the Cantabrian Mountains (e.g. Alonso and Marcos, 1992; Alonso and Teixell, 1992; Bulnes and Marcos, 2001; Bulnes and Aller, 2002).

Cross section validation

In order to validate the constructed cross section, it was restored to the pre-deformed stage (Fig. 3b). The evidences of layer-parallel shear (e.g. shear veins within bedding showing striations and slickensides approximately perpendicular to the fold axes) suggested employing this algorithm in the restoration process, although the equal-area restoration algorithm was used in zones where local thickness variations occur. The pin and loose lines were placed perpendicular to bedding in the unfolded, but transported along the detachment, footwall and hangingwall blocks respectively. In order to carry out the restoration, a forward sequence of thrust emplacement was assumed. The restoration obtained is reasonable from a geometrical and geological point of view, since it consists of a detachment from which an imbricate thrust system emanates with ramps dipping around 10 to 30° and, therefore, validates the geological interpretation of the structure. The shortening values obtained from the restoration for different horizons vary from 4.53 to 3.18 m (25.2 to 19.1%).

Deformation simulation

A deformation simulation was carried out using a technique that provides strain parameters of deformation derived from strain markers placed strategically in the deformed, present-day cross section subsequently restored (Masini *et al.*, *submitted*).

Figures 5a and 5b show the orientation of the maximum and minimum elongation and the orientation of the lines of no finite deformation calculated for each strain marker on the deformed, present-day section across Los Fuejos structure. In the hangingwall block, close to the thrust ramp where faults *a*, *b*, *c* and *d* merge, the orientation of the strain elements simulated is compatible with the architecture of the small-scale structures observed in the outcrop (cleavage surfaces sub-perpendicular to the minimum elongation, tension gashes sub-perpendicular to the maximum elongation, movement along bands of en echelon tension gashes compatible with the orientation of maximum and minimum elongation, and one set of lines of no finite deformation sub-parallel to the shear veins and to the bedding undergoing layer-parallel shear). In the hangingwall block, the maximum and

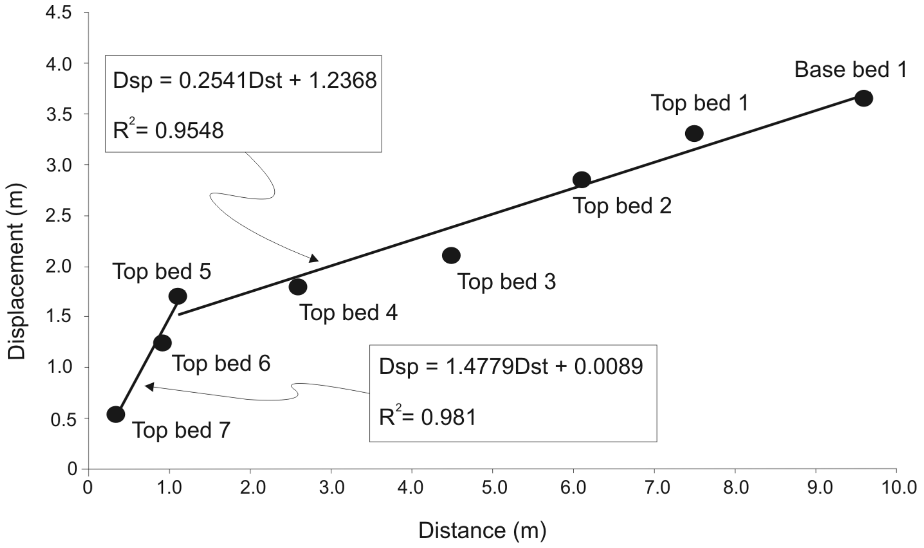

Figure 4. Displacement vs. distance graph for fault *a* in figures 2c and 3. The gentle-slope function on the right side of the diagram is the best-fit linear function calculated from the bed 1 base to the bed 5 top, whereas the steep function on the left side is the best-fit linear function for the top of beds 5, 6 and 7. The equations for both functions are displayed, in which Dsp and Dst are the displacement and the distance respectively and R^2 is the coefficient that indicates how well the linear functions fit the available data.

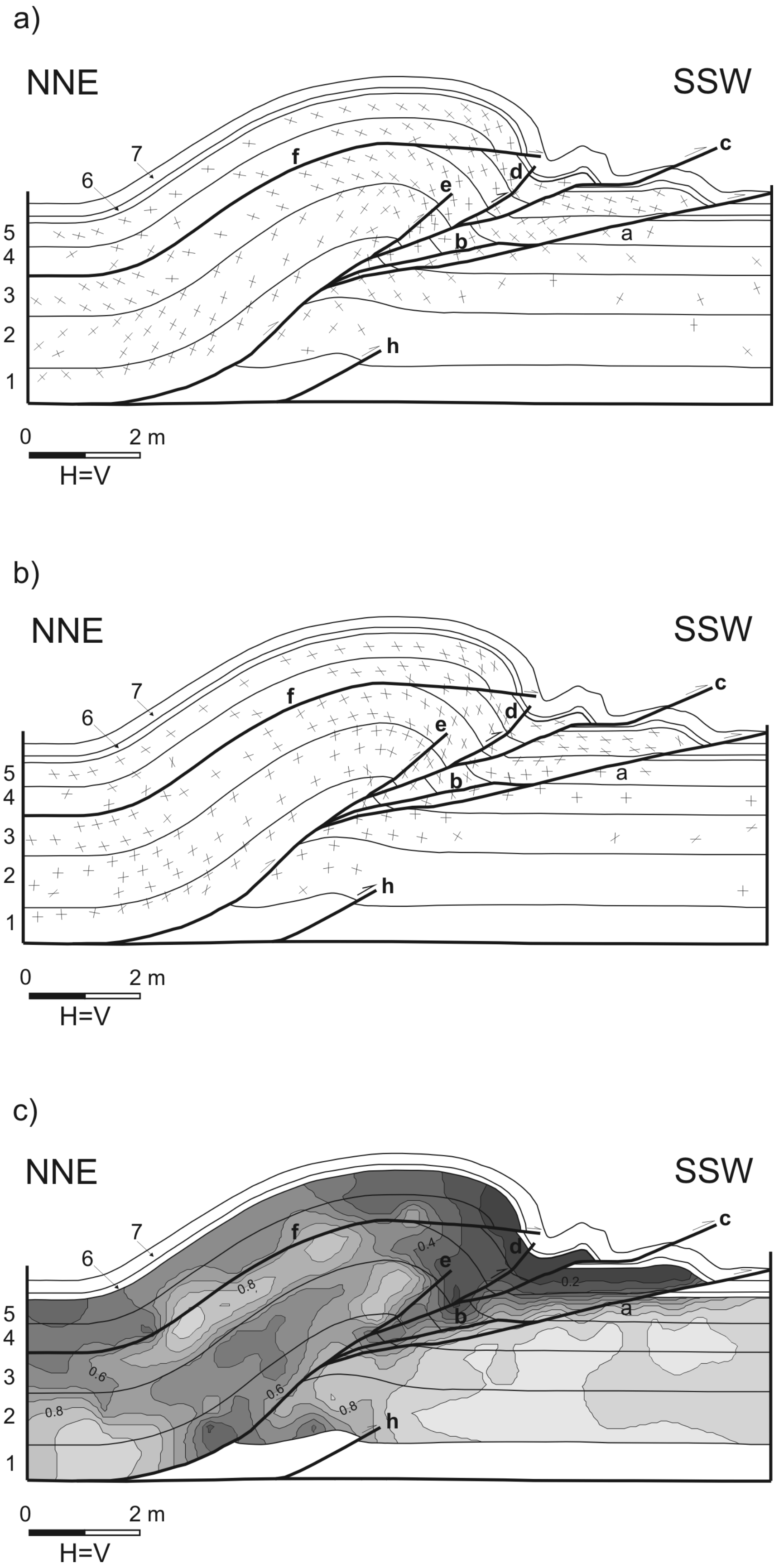

Figure 5. Deformation simulation of Los Fuejos fault-propagation fold including: (a) orientation of maximum and minimum elongation for each strain marker; (b) orientation of lines of no finite deformation for each strain marker; (c) contour map (obtained using the kriging interpolation algorithm) of ellipticity coefficient values (minimum/maximum elongation ratio) being the contour interval 0.1. The maximum deformation is represented by dark colours with values tending to zero, whereas the minimum deformation is represented by light colours with values close to one. The fact that the contours are not offset by the faults does not necessarily mean that ductile deformation postdates faulting, but to the superposition of the contour map on top of the present-day cross-section.

minimum elongation show dips in opposite senses in beds number 3, 4 and 5 with respect to beds 1 and 2 (Fig. 5a). Such anomaly is probably due: (i) to the geometric modification of the structure introduced when the fault *g* with out-of-plane movement was removed from the cross section (Fig. 2c), (ii) the displacement along fault *f*, and/or (iii) the irregular geometry of the restored loose line (Fig. 3b); however, this anomaly is insignificant because of the small amount of deformation deduced for this area (Fig. 5c). Such anomaly would be consistent with the hypothesis of shear induced by fault g due to its displacement as a backthrust.

Figure 5c shows a contour map constructed through the interpolation of the ellipticity coefficient values (minimum elongation/maximum elongation ratio) calculated for each strain marker. The maximum deformation is concentrated in a triangular zone in the anticline forelimb and in the frontal syncline, whereas the anticline backlimb shows moderate deformation and the unfolded footwall block shows negligible deformation. Such results are similar to those obtained in the trishear model proposed by Erslev (1991), and Allmendinger (1998) amongst others, or other mechanisms (Alonso and Teixell, 1992).

Conclusions

The structure studied here, called Los Fuejos, involves mainly Carboniferous limestones and is located in the Cantabrian fold and thrust belt (NW Iberian Peninsula) in the northern limb of the regional-scale Villasecino anticline (Bodón structural unit). Field measurements and observations as well as the results obtained from the displacement vs. distance diagram permitted to classify the structure as a fault-propagation fold related to a south-directed imbricate thrust system. A restoration carried out using layer-parallel shear (and equal-area balancing where local variations of thickness occurred) validated the geological interpretation and supplied shortening values comprised between 4.53 and 3.18 m (25.2 to 19.1%). The simulation of deformation performed exhibits maximum deformation concentrated in a triangular zone in the anticline forelimb and in the frontal syncline, moderate deformation in the anticline backlimb and negligible deformation in the unfolded footwall, in accordance with the structural features of fault-propagation folds developed using the trishear model and confirming the validity of such analysis. The simulated strain architecture is compatible with the orientation of the small-scale structures observed in the outcrop (shear veins, en echelon tension gashes and cleavage).

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