Syn-thrusting, near-surface flexural-slipping and stress deflection along folded sedimentary layers of the Sant Corneli-Bóixols Anticline (Pyrenees, Spain).

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Keywords: Growth strata; thrust-related anticline; stress; unconformity; flexural-slip.

Abstract

In the Spanish Pyrenees the Sant Corneli-Bóixols thrust-related anticline displays an outstandingly preserved growth strata sequence. These strata lie on top of a major unconformity exposed at the anticline's forelimb that divides and decouples a lower pre-folding unit from an upper syn-folding one. The former consists of steeply-dipping to overturned strata with widespread bedding-parallel ~~shears~~slip indicative of folding by flexural-slip, whereas the syn-folding strata above define a 200-m amplitude ~~S-shaped~~ fold. In the inner and outer sectors of the forelimb, both pre- and syn-folding strata are near-vertical to overturned and the unconformity angle ranges from 10° to 30°. In the central portion of the forelimb, syn-folding layers are ~~shallowly~~gently-dipping, whereas the angular unconformity is about 90° and the unconformity surface displays strong S-C shear structures, which provide a top-to-the foreland ~~shear~~slip sense. This sheared unconformity is offset by steeply-dipping faults which are at low angles to the underlying layers of the pre-folding unit. Strong shearing along the unconformity surface also occurred in the inner sector of the forelimb with S-C structures providing an opposite, top-to-the hinterland, ~~shear~~slip sense. Cross-cutting relationships and ~~shear~~slip senses along the pre-folding bedding surfaces and the unconformity indicate that regardless of its orientation, layering in the pre- and syn-folding sequences of the Sant Corneli-Bóixols anticline was continuously ~~sheared~~slipped. This ~~shearing~~slipping promoted an intense stress deflection, with the maximum component of the stress tensor remaining at low angles to bedding~~s~~ during most of the folding process.

1. Introduction

Templates used to describe the state of stress of growing regional-scale thrust-related anticlines (e.g. Hancock, 1985; Lisle, 1994; Fischer and Wilkerson, 2000; Belayneh and Cosgrove, 2004; Tavani et al., 2015), typically integrate punctual strain data (e.g. Engelder and Geiser, 1980; Laubach, 1989; Lacombe, 2012; Balsamo et al., 2016) and indirect information provided by the large-scale geometry of the structure, such as like curvature or strata thinning/thickening (e.g. Price and Cosgrove, 1990). Widespread documentation of bedding-parallel slip, along with the ~~broad~~ preservation of layer thickness, provide key information ~~to model~~for modelling the distribution of stress in actively growing anticlines. These observations indicate flexural-slip folding in the multilayered portions of reservoir-scale thrust-related folds (e.g. Donath and Parker, 1964; Ramsay; 1967; Tanner, 1987; Suppe, 1983; Fowler, 1996; Erslev and Mayborn, 1997). The assumption/observation of flexural-slipping has important consequences ~~on~~for the stress distribution:

- ~~Shearing~~Slipping along numerous bedding surfaces within~~in~~ a wide range of bedding dip, is possible only where the bedding surfaces have a low friction and a low cohesion.
- On the other hand, the reactivation of these closely spaced low friction surfaces should prevent the layer-parallel shear stress to exceed a certain value, which in turn ~~imposes~~constrains the direction of the maximum component of the stress field to be at low angle to bedding, i.e. at low angle to the ~~shearing~~slipping surface (Wiltschko et al., 1985; Ohlmacher and Aydin, 1997; Tavani et al., 2015).

The process of layer-parallel ~~shearing~~slipping is, however, discontinuous in time and space, so that it is unclear whether the regional stress reorients only locally or, rather, the layer-parallel slipping is sufficiently dense, both in time and space, to promote the reorientation of the stress in wide - actively folding - areas. Field documentations are in agreement with the second hypothesis, i.e. that ~~shearing~~slipping along low-friction bedding surfaces promotes deflection of the principal directions of the remote stress field, ~~with~~so that the direction of the maximum compressive stress ~~keeping~~maintains at low angle to ~~layers~~the bedding, so that the maximum stress in active fold and thrust belts may not be ~~not~~ always strictly horizontal. In fact, syn-folding layer-parallel shortening structures are reported in the folded pre-growth strata of many thrust related anticlines (e.g. Tavani et al., 2006; 2012). However, paleo-stress and/or paleo-strain indicators cannot easily and unequivocally constrain the bedding dip values range at which such stress deflection mechanism can operate (e.g. Callot et al., 2010; Beaudoin et al., 2012). In fact, almost all published datasets come ~~uniquely~~ from pre-growth sequences of thrust-related folds. In these cases, ~~deciphering for which bedding dip values~~ determining the bedding dip when a given set of deformation structures are formed (i.e. fractures or slickenlines along a bedding surface) remains difficult, and any assumptions made carry along significant uncertainty.

On the other hand, observations made in syn-growth layers of thrust-related anticlines ~~allow~~serve to drastically reducing uncertainties related to the timing of deformation (e.g. Shackleton et al, 2005, 2011). In~~As a matter of~~ fact, the study of growth strata sequences are by far the most commonly used approach for understanding the kinematics of fault-related folds in contractional settings (e.g. Suppe et al., 1992; Burbank et al., 1996; Ford et al., 1997; Suppe et al., 1997; Vergés et al., 2002). In contrast with the abundance of detailed geometrical studies (Suppe, 1983; Medwedeff, 1989; Mitra, 1990; Suppe and Medwedeff, 1990; Zapata and Allmendinger, 1996; Poblet et al., 1997; Suppe et al., 1997), only a few contributions dealing with the dynamics of folding inferred from syn-kinematic layers have been published (e.g. Ford et al., 1997; Nicol and Nathan, 2001; Shackleton et al., 2011; Beaudoin et al., 2015), mostly because of the lack of well-preserved and accessible exposures. In this work we have focused on the macro- and meso-structures developed within a growth strata wedge and a related major syn-kinematic unconformity exposed at the forelimb of the Sant Corneli-Bóixols anticline. Bedding-parallel ~~shear~~slip occurs along pre- and syn-kinematic strata, which are oriented obliquely to each other, together with meso-scale faults cutting across strata and the unconformity. Thus, this area provides an excellent, almost unique, field example to observe, describe, and analyse how oblique anisotropies ~~oblique to each other~~, i.e. layers and unconformity, respond to progressive shortening and related folding in a contractional setting. In addition, the studied area allowed us to determine the threshold dip value at which flexural-slip is of sufficient magnitude to deflect the maximum principal stress direction from the regional stress field.

2. Geological Setting

The Pyrenean Belt is a doubly-vergent orogenic wedge (Fig. 1a) formed during the Late Cretaceous to Miocene subduction of the Iberian lithosphere beneath the Eurasian plate (e.g. Choukroune et al. 1990; Muñoz, 1992; Teixell, 1998). It largely deformed and inverted the Mesozoic extensional basins developed between Iberia and Eurasia during the Mesozoic separation of these two plates (Muñoz, 2002). The Early Cretaceous Organyà basin is one of these basins interposed between the Iberian plate and the exhumed mantle of the Pyrenean rift (e.g. Tugend et al., 2014). Upon convergence and shortening, the Organyà basin was positively inverted and incorporated into the hanging-wall of the Bóixols thrust starting on Late Cretaceous times (e.g. Mencos et al., 2015 and references therein). The positive inversion of the inherited extensional structures occurred under oblique, NNW-SSE oriented, convergence (Tavani et al., 2011), and was responsible for the development of the E-W striking Sant Corneli-Bóixols anticline (Fig. 1a). The location and geometry of this anticline is controlled by the orientation of the Early Cretaceous extensional border fault system of the Organyà basin (e.g. Bond and McClay, 1995; García-Senz, 2002; Mencos et al., 2015).

Several detailed studies of the stratigraphy of the Organyà basin ~~were~~have been carried out in the last 50 years (e.g. Rosell, 1963; Garrido; 1973; Simó, 1986; Berástegui et al., 1990; García-Senz; 2002, Mencos, 2011). The pre-rift Mesozoic stratigraphy is represented by clays and evaporites belonging to the Triassic Keuper facies, followed by Jurassic shallow marine carbonates and deeper water marls. The Early Cretaceous syn-rift megasequence consists of platform carbonates that thicken towards the north and ~~transition~~change laterally (i.e. toward the north) into basinal marls (e.g. García-Senz, 2002). In the hanging-wall of the Bóixols thrust the maximum thickness of the syn-rift megasequence is about 4500m. It thins southwards around the hinge zone of the Sant Corneli-Bóixols anticline across the extensional fault system at the southern margin of the Organyà basin (Lanaja et al., 1987; Berástegui et al., 1990; Arbués et al., 1996; García-Senz, 2002; Muñoz et al., 2010; Mencos et al., 2015). The Upper Cenomanian to Lower Santonian post-rift megasequence consists of carbonates with lesser clastics and can be up to 700m thick (García-Senz, 2002; Mencos, 2011). The syn-orogenic strata are exposed in the leading syncline (i.e. Tremp-Sallent Syncline) of the Sant Corneli-Bóixols anticline (Fig. 1a-b) and include more than 1000m of Upper Santonian to Paleocene deepwater to continental strata that thin abruptly to a few tens of meters northwards, i.e. towards the Sant Corneli-Bóixols anticline (e.g. Arbués et al., 1996; Roma et al. 2011).

In the studied area, the syn-orogenic succession can be subdivided into two units (Figs. 1b-c): (1) The lower, Upper Santonian to Campanian, Vallcarga Group (Nagtegaal, 1972) is constituted by a multilayered marine sequence of thin to medium bedded limestones and mudstones. Around the Sant Corneli-Bóixols Anticline the Vallcarga Group was deposited during folding as evidenced by growth geometries at the eastern tip of the Sant Corneli Anticline (Mencos et al., 2015). However, no clear ~~evidences~~indications of deposition during the early stages of folding are visible in the studied area and hence it is here geometrically considered as pre-kinematic but within a regional syn-orogenic scenario. (2) The Late Campanian to Maastrichtian Areny Group (Arbués et al., 1996) is unconformably overlying the Vallcarga Group. Its thickness exceeds 1000m in the Tremp-Sallent Syncline depocentre (Fig.1a-b) but thins abruptly to a few tens of meters towards the Sant Corneli-Bóixols Anticline so it is considered to have been deposited during folding (i.e. syn-folding). The Areny Group records sedimentation in neritic to deep marine conditions coeval with the inversion and related folding of the Organyà extensional basin. The Areny Group has been divided into four sequences (A1 to A4 from older to younger; Arbués et al., 1996) and broadly includes rudist accumulations and talus marls, sandstones, and re-sedimented equivalent in turbiditic facies. (3) The syn-folding Maastrichtian to Paleocene Tremp Group (Cuevas, 1992) includes continental facies associations which are commonly referred to as the Garumnian facies (Cuevas, 1992). These consist of alluvial and colluvial conglomerates and breccias, passing southwards to alluvial plain and fluvial reddish sandstones and mudstones (e.g. Arbués et al., 1996; Roma et al., 2011).

From a structural point of view, the major structures in the studied area are the Bóixols thrust and related splays, the E-W trending Sant Corneli-Bóixols Anticline and the associated Santa Fe Syncline to the north and the Tremp-Sallent Syncline to the south (Fig. 1a). The main ramp of the Bóixols thrust crops out in the studied area, whereas to the west and to the east it remains blind along most of the frontal limb of the Sant Corneli-Bóixols Anticline. In its exposed sector, the Bóixols thrust has Triassic to Upper Cretaceous pre-growth rocks in its hanging-wall and syn-orogenic and syn-folding strata in its footwall (Fig. 1c). A thin sheet of overturned post-rift limestones, mainly the upper Cenomanian ones, defines two thrusts. The lower thrust remains blind beneath the vertical beds of the Garummnian succession ~~at~~ on the northern limb of the Sallent Syncline. The upper ~~one~~thrust on the other hand truncates the Garumnian beds. This upper one is the Bóixols thrust and according to magnetostratigraphic and thermochronological studies it would have been reactivated during Paleogene times (Beamud et al., 2011). The pre-folding beds of the Vallcarga Group in the footwall of the Bóixols thrust are folded into a syncline with overturned strata immediately below the thrust fault. These strata progressively acquire sub-horizontal attitudes in the Tremp-Sallent Syncline to the south (Fig. 1c). Conversely, the unconformably overlying Areny and Tremp Groups display a series of folded structures, namely the Sant Maximí Syncline and the Tremp-Sallent Syncline, with the Remolina Anticline in between. The Remolina Anticline disappears toward the east, where the two synclines join (Fig. 1b). The three folds display a significant eastward plunge (Roma et al., 2011) of 24° with a N72° ~~strike~~plunge direction, as derived by the direction normal to the best fit plane of bedding data of the Areny Group (Fig. 1c).

These poles to bedding are well clustered along a great circle, thus defining the axis of a cylindrical fold. This suggests that the plunge was acquired after the deposition of the syn-folding Areny Group. In addition, it is to be noted that poles to pre-folding bedding are clustered along the same great circle, indicating that the folding axis was parallel to the intersection between the pre-unconformity beds and the unconformity (Ramsay, 1967).

3. Macro- and Meso-structures

In the following, we describe the structural assemblages occurring along and around the major unconformity dividing the Areny from the Vallcarga Group, i.e., the lower syn-folding strata from the upper syn-folding strata (Fig. 1d). The macro- and meso-structures are described from north to south in three sub-sections, corresponding to the three limbs of the S-shaped fold that define the Sant Maximí Syncline, the Remolina Anticline, and the Tremp-Sallent Syncline (Fig. 1). We will present and discuss stereoplots of bedding attitude, fault orientations and kinematic indicators from faults. In these stereoplots the plane normal to the structural plunge is also displayed, in order to ease the interpretation of the faults kinematics. For each stereoplot, we also show the two graphs resulting from the removal of plunge first and then of the residual bedding dip (Ramsay, 1967).

3.1 Northern limb

~~In~~On the inner (northern) limb of the Sant Maximí Syncline, the marls and limestones of the Vallcarga Group are overturned, while the unconformably overlying strata of the Areny Group are steeply south-dipping to near-vertical (Fig. 2). In the northern limb of the syncline, the strata of the Areny Group include siltstones, sandstones, and conglomerates belonging to the A4 sequence; the A1 to A3 sequences are missing (Fig. 2a-b), either because they were never deposited there or because they have been eroded before the deposition of the A4 sequence. Overturned bedding surfaces of the Vallcarga Group display evidence of ~~shearing~~slipping. Movements along bedding are mostly toward the NW with normal sense of slip in the present overturned bedding orientation (Fig.

2b). Stereoplots show that slickenlines along bedding surfaces of the Vallcarga Group are mostly perpendicular to the local fold axis. The unconformity between the Vallcarga and the Areny Groups has been reactivated as a thrust and displays an intense S-C fabric that affects a few meters of the Vallcarga Group (Fig. 2c). Analogously to other S-C tectonites developed in carbonates and at shallow depth (e.g. Tesei et al., 2013; Vitale et al., 2014), the S-C structures found in the first 2-3 m of the Vallcarga Group immediately below the unconformity, formed as consequence of pressure-solution of marly limestones and marls, and thus indicating a ductile to brittle-ductile behaviour of the Vallcarga Group ~~in correspondence of~~associated with this major fault. Slip directions provided by C, S and C' structures are top-to-the-NW and, similarly to the bedding-parallel slip surfaces, the average slip direction lies along the plunge-normal plane (Fig. 2c). The Areny Group conglomerates immediately above the unconformity are not affected by S-C fabric, whereas siltstones occurring few meters above the unconformity are affected by a strong cleavage (Fig. 2d). This cleavage is at a high angle to bedding, as seen in the field and as evidenced by the fact that poles to cleavage in the stereoplot occur close to the bedding planes great circles (Fig. 2d). However, cleavage is not strictly bedding-perpendicular. Once bedding dip is restored to the horizontal, the poles to cleavage still ~~lay~~lie along the plunge normal-plane and cleavage becomes SE-dipping. These relationships are indicative of a minor top-to-NW ~~shear~~slip component during cleavage development. It is worth remarking that, despite the importance for stress direction reconstruction, the above described cleavage is a localised feature, which affects only the silty beds of the uppermost portion of the Areny Group in some outcrops.

3.2 Central limb

Immediately to the south of the axial surface of the Sant Maximí Syncline, strata of the Areny Group are shallow dipping to sub-horizontal (Fig. 1c-d). Locally, however, strata of the A4 sequence of the Areny Group are steeply north-dipping and the Sant Maximí Syncline forms a tight structure with a north-dipping to near vertical axial surface. In the hinge zone, the unconformable strata of the Areny Group are separated from the underlying overturned strata of the Vallcarga

Group by a sub-horizontal ~~shear~~slip zone, which corresponds to the sheared syn-folding unconformity (Fig. 3). In addition, the sheared unconformity is offset by a series of high-angle faults that uplift the southern block (Fig. 3b). Striae along bedding surfaces of the Vallcarga Group indicate top-to-N movements with normal kinematics (Fig. 3b). Striae within the sub-horizontal ~~shear~~slip zone indicate top-to-S movement, whereas the high angle faults that offset it have slickenlines lying along the plunge-normal plane and show a top-to-N movement. A few strike-slip slickenlines also occur along high angle faults, and are indicative ~~for~~of left-lateral movements. In other places, the system of high angle reverse faults uplifting the southern limb of the Sant Maximí Syncline displays a top-to-NW movement, including some right-lateral kinematic indicators (Fig. 3c). Looking at the system of high angle faults in natural cross-sections at a larger scale of observation (Fig. 3c), it is evident that these faults are approximately (i.e. angular difference is less than 10°) parallel to the ~~layers~~bedding of the Vallcarga Group, and that the amount of uplift of the southern block is a few tens of metres.

The uplifted southern block is well exposed at the Sallent hill (Fig. 4). There, the sub-horizontal rudist-bearing units of the Areny Group A3 sequence sit unconformable on top of the overturned north-dipping strata of the Vallcarga Group (Fig. 4a-b). Slickenlines are consistently found along the bedding surfaces of these strata. As shown in the stereoplots of Figure 4a, most of slickenlines display top-to-N normal kinematics, whereas a few are characterised by strike-slip (both left- and right-lateral) or reverse kinematics. The slickenlines displaying strike-slip and reverse kinematics postdate the top-to-N normal ones. Faults oblique to bedding have been also found in the Vallcarga Group in this area (Fig. 4a). These faults are at low angle with the bedding surface and display normal and, subordinately, reverse kinematics. After bedding dip removal, both bedding-parallel ~~shear~~slip surfaces and bedding-oblique faults, show a top-to-NW ~~shear~~slip sense. As mentioned above, strata of the rudist-bearing A3 sequence are shallow dipping (Fig. 4a-b) and the unconformity between the Areny and the Vallcarga groups is also sub-horizontal. The unconformity is affected by a pervasive shear fabric (Fig. 4c) with S, C, and C' structures providing a top-to-SSE shear sense. In addition, the sheared unconformity is cross-cut by SSE-dipping and NNW-verging reverse faults (Fig. 4b).

3.3 Southern limb

On the southern limb of the Remolina Anticline, ~~S~~strata of the Areny Group are overturned to ~~mostly~~ steeply south-dipping ~~to the south of the Remolina Anticline, strata of the Areny Group are overturned to mostly steeply south-dipping~~ (Fig. 5a). These strata are still unconformable on top of the overturned strata of the Vallcarga Group, but the unconformity angle between the two groups becomes significantly reduced ~~down~~ to about 20°. The unconformity preserves its stratigraphic origin and, as opposed to the northern and central limbs of the Sant Maximí syncline, no appreciable evidence of shear occurs (Fig. 5b). Instead, striae along the bedding surfaces of the Areny Group are observed (Fig. 5c). These striae indicate normal top-to-NNW and reverse top-to-NNE movements along north-dipping overturned and steeply south-dipping strata, respectively (Fig. 5c). In both cases, striae lie along the bedding surfaces at the intersection between bedding and the plunge-normal plane (Fig. 5c). Faults at a low angle to bedding have the same behaviour as the bedding: south- and north-dipping faults are reverse and normal, respectively, with slickenlines lying at the intersection between the fault and the plunge normal plane (Fig. 5c). Once bedding dip is restored to the horizontal, a top-to-NNW ~~shear~~slip sense is ~~provided~~exhibited by both faults and bedding-parallel ~~shear~~slip surfaces.

3.4 Structural summary

The deformation structures observed along and around the unconformity separating the upper syn-folding strata of the Areny Group from the underlying multilayered limestones and marls of the Vallcarga Group can be summarised as follows:

In the Vallcarga Group, many of the E-W striking bedding surfaces of near-vertical to overturned strata have been reactivated as ~~shear~~slip surfaces. Most of these bed-parallel ~~shear~~slip surfaces exhibit dip-slip kinematics, with only a few beds showing strike-slip movements. After removing the plunge of the structure and then restoring the local bedding to the horizontal, most of the slickenlines measured along the bedding surfaces provide a ~~shear~~slip sense ranging from top-to-NW to top-to-N, with an average top-to-NNW movement. Faults are roughly E-W to WSW-ENE striking and show very low cut-off angles to bedding. After removing the fold plunge and the bedding dip, these faults provide the same top-to-NNW ~~shear~~slip sense as the bedding-parallel slickenlines. Some faults, which are presently steeply dipping to near vertical, have cut-off angles of ranging from 20° to 40° and after removing plunge and bedding dip show normal kinematics. Still, the ~~shear~~slip sense provided by them after bedding dip removal is top-to-NNW. This fault pattern and the illustrated kinematics of bedding surfaces is observed all across the studied thrust-related fold profile, i.e. in the northern, central, and southern limbs.

The syn-folding unconformity is characterised by an intense S-C fabric (showing also some C' structures) in the northern limb, and in the sub-horizontal central limb. In both cases, ~~shear~~slip direction is roughly NNW-SSE, although some strike-slip movements are occasionally observed. However, the ~~shear~~slip sense is opposite in the two limbs, being top-to-NNW in the northern limb (i.e., where the sheared unconformity strikes about E-W and has a near vertical attitude) and top-to-SSE in the central limb (i.e., where the sheared unconformity is offset by the steeply-dipping to near vertical faults surging from the underlying Vallcarga Group). Further to the south, in the southern limb of the Remolina Anticline, the unconformity shows little evidence of deformation.

Strata of the Areny Group exposed at the northern limb of San Maximí Syncline are affected by an intense cleavage at high angle to bedding. The cleavage-bedding angle is not exactly 90° however, indicating the occurrence of a top-to-NNW bedding-parallel ~~shear~~slip component. Slickenlines are observed along the bedding surfaces of the near vertical to overturned strata of the Areny Group exposed at the southern limb of the Remolina Anticline. In this area, some faults at very low angle to bedding occur. For both faults and bedding surfaces, the ~~shear~~slip sense measured after removing the plunge and the dip of the bedding is roughly top-to-NNW.

4. Chronology of deformation stages

The syn-folding strata of the Areny Group exposed at the forelimb of the Sant Corneli-

Bóixols Anticline are unconformably ~~on top of~~overlying the north-dipping overturned strata of the pre-folding Vallcarga Group. The unconformity between both groups is clearly a syn-folding feature. Its unconformity angle varies across the studied area, and in addition, its surface shows unequivocal evidence of strong shearing with an average NNW-SSE-oriented shear direction. Such a shear direction is parallel to the slip directions measured along both faults and bedding surfaces of the Vallcarga and Areny groups. However, ~~T~~the NNW-SSE direction is not perpendicular to the average strike of the hosting anticline~~ tough.~~, although the local fold axis in the study area is WSW-ENE striking (Fig. 1a). This structural relationship reaffirms that the E-W striking Sant Corneli-Bóixols Anticline has developed under an oblique convergence setting where the shortening direction was NNW-SSE (Tavani et al., 2011). In this sense, the observed meso-structures are interpreted as developed during the growth of the Sant Corneli-Bóixols Anticline, and they cannot be attributed to a subsequent tectonic event. The fact that these structures occur in syn-folding strata, also rules out a pre-folding origin. In agreement with this, the observed opposite shear senses along the unconformity surface to the north and to the south of the San Maximí Syncline axial surface have a syn-folding origin. As illustrated in the next section these opposite senses of ~~shear~~slip can be used to unravel the kinematic evolution of the unconformity, the unconformity angle itself and therefore that of the Sant Corneli-Bóixols Anticline.

5. Modelling the folding of the angular unconformity

Guidelines about flexural-folding of angular unconformable sequences w~~h~~ere firstly ~~provided~~given by Alonso (1989). These include the progressive variation of the unconformity angle during tilting of pre-unconformity layers, synchronously with progressive ~~shearing~~slipping along the unconformity surface (Alonso, 1989). Figure 6a illustrates the folding of an unconformable sequence using a kink-band template with synclinal geometry. The position of six ~~key~~ points undergoing folding is illustrated~~,~~. ~~where the fixed~~ The points P_0 and P_1 ~~point~~ are fixed and inactive, i.e. they do not move during folding and the rock does not pass through them. The point P_1 is the origin of our reference system. The point P_2 is located at the intersection between the axial surface and the unconformity and, as the axial surface moves during folding, this point is an active point that migrates through the rock. The remaining points are mobile but inactive material points, which are attached to the rock. In detail, the points P_3 and P_5 are attached to the base of the post-unconformity unit, while the point P_4 is immediately below the unconformity, and it is attached ~~at~~to the layer corresponding to the stratigraphic elevation of the point P_0. The simple kink-band construction is used to quantify how the unconformity angle and the amount of ~~shear~~slip along the unconformity are modified during folding, where D_0 is the initial dip of layers, U_0 the initial unconformity angle, H_0 the stratigraphic elevation of the unconformity, and L_0 the distance from the origin of an arbitrarily placed pin line (note that the L_0 parameter will disappear from the final equations used here). The X and Y coordinates of the 6 key points and the length of the segments joining them can be expressed as a function of L_0, H_0, U_0, D_0, and D, as provided in figure 6b. In particular, the length of the segment joining points P_5 and P_4 provides the amount of ~~shear~~slip (ΔS, considered positive when top-to-the-hinterland), while points P_3 and P_4 allow calculating the unconformity angle (U).

As folding takes place, the unconformity angle increases and the ~~shears~~ sense of slip along the unconformity is initially top-to-the-hinterland, i.e. in the same sense as the flexural-slip along the pre-unconformity layers. When the pre-unconformity strata become overturned, the unconformity angle continues to increase and the flexural-slip in the pre-unconformity layers continues to be top-to-the-hinterland; instead the ~~shear~~ sense of slip along the unconformity flips and becomes top-to-the foreland. Close to the leading syncline, i.e. along the P_2P_3 segment, the sense of the incremental ~~shear sense~~slip is top-to-the-hinterland, whereas along the P_3P_4 segment it becomes to top-to-the-foreland, despite the cumulative ~~shear sense~~slip may continue to be top-to-the-hinterland.

The relationship between U, U_0, and D derived in figure 6b, are graphed in figure 6c. The relationships between U on D (blue lines in the figure) for different U_0 values, indicate that:

(1) It is possible to develop overturned pre-folding strata and a nearly sub-horizontal

unconformity, as observed in the central limb of our study area, (i.e. the unconformity angle is roughly equal to the dip of the pre-unconformity layer) for a wide range of initial unconformity angles (from 30° to 90°).

(2) In order to obtain an unconformity angle of less than 20° where the pre-unconformity strata are near vertical, as observed in the northern and southern limbs of the study area, the initial unconformity angle cannot exceed 10-15°.

The predicted amount and sense of ~~shear~~slip (normalised to H_0) at different tilting stages (i.e. for different D) and for different initial unconformity angles (i.e. U_0) is plotted in red in figure 6c, where positive and negative values indicate top-to-the-hinterland and top-to-the-foreland ~~shear~~slip, respectively. For small initial unconformity angles, the unconformity angle and the cumulative top-to-the-hinterland slip along the unconformity increase during folding. This occurs until the dip of pre-growth strata attains a near-vertical attitude. From this point, further folding would imply overturning of strata and the decrease of the cumulative top-to-the hinterland slip, which eventually becomes negative (i.e. top-to-the-foreland sense), while the unconformity angle U exceeds 90° Where the initial unconformity angle is instead close to 90°, progressive folding would imply a short period of top-to-the-foreland ~~shearing~~slipping along the unconformity, followed by top-to-the hinterland ~~shearing~~slipping when strata become nearly vertical to overturned. At this point it is important to remark that the progressive and the incremental ~~shear~~slip senses do not coincide. The D value at which the cumulative ~~shear~~slip passes from top to the hinterland to top-to-the-foreland largely depends on the initial unconformity angle U_0. Conversely, for an initial unconformity angle U_0 between 45° to 90° the incremental ~~shear~~slip changes its sign for values of D ranging from 80° to 90°, and almost regardless on U_0, value (the regions where the incremental ~~shear~~slip has opposite directions are in white and grey in figure 6c).

The absence of any kinematic indicator of top-to-the-hinterland ~~shear~~slip in the central limb of the study area, indicates that the initial unconformity angle had to be high at that position, and if any, the initial stage of top-to-the-hinterland ~~shearing~~slip was negligible. This can be achieved when the initial unconformity angle is at least 70-75°. This represents a key argument for unravelling the deformation sequence, as structures postdating the top-to-the foreland ~~shearing~~slipping have to be interpreted as developed synchronously with layers' tilting, and in particular, as developed at least after layers have become near vertical. The top-to-the hinterland ~~shear~~slip sense and the small unconformity angle observed in the northern limb, instead, point out for a small initial unconformity angle.

It is worth noting that the position of the axial surface is determined by the position of P_0, and thus by the value of L_0 and H_0. These two parameters do not influence the value of the unconformity angle. Instead, the amount of slip is directly proportional to the value of H_0. However, we are interested in the sign of the slip, which is independent on H_0. In agreement, provided results are unrelated to the position of the axial surface, and thus of P_0, which can be arbitrarily set everywhere below the unconformity.

A cautionary note must be added for these conclusions, as they are based on a purely geometric model, in which both bed thickness and line length ~~preserves~~ are preserved during folding. However, and despite the occurrence of local penetrative strain at some places (Fig. 2d), based on the field observation reported here and in Tavani et al (2011), pressure solution cleavage is an extremely localized phenomenon in this anticline, and deformation structures pointing out for folding-related bed thickness variations are not occurring. In agreement, and despite the intrinsic simplification of any geometric model, information provided by the model of figure 6 can be applied to our case study.

6. Discussion

6.1 Relative timing between ~~shearing~~slipping and layers' tilting

Strata of the Vallcarga Group exposed at the forelimb of the Sant Corneli-Bóixols Anticline display a rather constant attitude~~, –~~. H~~h~~owever, according to the model described in figure 6, ~~shear~~slip senses and angles of the unconformity on top of these strata, indicate that the pre-unconformity layers (i.e. the Vallcarga Group) were not homoclinally-dipping when the Areny Group was unconformably deposited on top them. The scheme of Figure 7a illustrates the present day simplified geometry of the studied structure, together with the balanced (i.e. line-length is preserved; Dahlstrom, 1969; Brandes and Tanner, 2014) reconstruction at a time immediately after the unconformity development. The reconstructed dip of pre-unconformity layers in the three limbs, is obtained according to what illustrated in section 5. As previously mentioned, the top-to-the-foreland shearing along the unconformity of the central limb has to be interpreted as occurring when strata of the Vallcarga Group attained a near-vertical to overturned attitude. On the other hand, the absence of any evidence of top-to-the-hinterland shearing along the unconformity surface at the central limb, ~~points out~~suggests that such an unconformity had to be developed when the layers of the Vallcarga Group were steeply dipping. In agreement with this, the north-dipping faults offsetting the sheared unconformity have to be regarded as syn-folding structures developed when strata of the Vallcarga Group were overturned. These 10- to 30-m spaced faults mostly consist of bedding-parallel segments (Figs. 4A and 5d), with some strands showing cut-off angles between 20° and 40° (see stereoplots of figures 3b-c), and are interpreted as flexural-slip faults, like those offsetting the topographic surface of growth folds (e.g. Burbank and Anderson, 2011; Gutiérrez et al., 2014; Li et al., 2015). These faults are therefore late-stage flexural-slip features and, as detailed in the next sub-section, cannot be compatible with a sub-horizontal maximum stress.

6.2 Maximum stress orientation

The studied natural stratigraphic units includes cm to m-thick strata of limestones, marls, sandstones and conglomerates exposed across an about 500-m-wide area (Fig. 1). The large number of strata involved in the deformation, coupled with their high compositional variability, prevents the collection of a representative dataset of friction and cohesion data of both layers and interlayers. It thus makes it impossible to carry out a quantitative dynamic (i.e. stress) reconstruction. However, many stress configurations can be easily discarded, due to their kinematic inconsistency with the observed shearing pattern. In particular, we consider that the maximum paleo-stress lies on the plane oriented perpendicular to the fault/flexural-slip plane and containing the slip direction, and forms an obtuse angle with the ~~shear~~slip sense (e.g. Etchecopar et al., 1981). The following observations can thus restrict the range of possible solution and the sources of stress during folding: (1) If we consider faults and strata in their present orientation and after plunge and bedding dip removal, the top-to-the-foreland layer-parallel ~~shearing~~slipping and the south-verging reverse faulting are rare features in the northern limb of the San Maximí Syncline, which is located at a distance of less than 100 m from the Bóixols thrust. The scarcity of these structures, and the occurrence of flexural-slip surfaces forming a low angle with the thrust and having an opposite ~~shear~~slip sense (i.e. normal kinematics), indicates the limited role of faulting-related stress, sourced from the process zone (e.g. Cowie and Scholz, 1992) of the upward propagating Bóixols thrust, in controlling the pattern of syn-folding ~~shearing~~slipping. This is contrary to what has instead been documented in other thrust-related anticlines (e.g. Bellahsen et al., 2006). (2) The top-to-the-hinterland (i.e. top-to-the-crest of the Sant Corneli-Bóixols Anticline) layer-parallel ~~shearing~~slipping observed along the bedding surfaces of the Vallcarga Group for all the three limbs has to be regarded as syn-folding. With the exception of few bedding-oblique strands of flexural-slip faults, no significant evidence of strata thinning/thickening has been observed in the Vallcarga group. This points out that, folding has been almost entirely produced by layer parallel-~~shearing~~slipping with bed-thickness preservation until late stage flexural-slip faulting took place (e.g. Donath and Parker, 1964). (3) Deformation structures such as the layer-(nearly) parallel shortening related cleavage measured in the silty levels of the Areny Group along the axial zone of the San Maximí syncline indicate a maximum stress oriented at a low angle to bedding (Fig. 2d). (4) The fourth key observation concerns the steeply-dipping faults, with high cutoff angles, cutting and displacing the unconformity. These faults include steps with cut-off angles of about 30° and steps parallel to the overturned bedding surfaces. Under the assumption that late-stage flexural slip faulting caused the arrest of shearing along the unconformity, a range of possible maximum stress orientation during the transition from top-to-the-foreland shearing along the unconformity to the late-stage flexural-slip faulting can be defined for the central limb, as shown in figure 7b. The angle between the maximum stress and the bedding-parallel steps of flexural-slip faults in the Vallcarga Group is α, the angle between the maximum stress and the flexural-slip fault strands oblique to bedding in the Vallcarga Group is β, whereas the angle between the maximum stress and the unconformity is γ. These three angles must be comprised between 0 and 90° to produce the observed ~~shear~~slip pattern and for it to be kinematically compatible. When using the average dip of the unconformity (i.e. 0°) and the dip of the Vallcarga Group strata in the central limb (i.e. 60° overturned), a maximum stress dip (labelled $d\sigma_1$ in figure 7d) ranging from 30° to 90° is obtained.

At this stage one may argue that the maximum stress was inclined only during the latest stage of folding, when pre-kinematic strata were overturned, while the maximum stress was sub-horizontal during most of the folding process. Such a scenario, in which the reorientation of the maximum stress is a discontinuous process, contrasts with the fact that, in order to produce ~~shearing~~slipping along bedding surfaces, the maximum stress should have been south-dipping not only when strata were 60° overturned. In fact, dip-slip ~~shearing~~slipping along upright layers also requires the maximum stress to be south-dipping, and such a stress configuration can be extrapolated also for steeply (e.g. >75°) south-dipping strata. In agreement, it is intuitive the conclusion that the stress rotation was not a discontinuous process, but instead it has continuously operated during folding.

As documented in Tavani et al (2011), the layer parallel shortening pattern in the the Sant Corneli-Bóixols Anticline indicates a sub-horizontal maximum stress before folding and during the early stages of folding. As evidenced by data presented here, the stress was in a configuration not allowing ~~shearing~~slipping (referring to faulting in the Vallcarga layers) during almost the entire folding process. Such stress configuration was able to produce ~~shearing~~slipping along the bedding surfaces and along the unconformity, with faulting in the Vallcarga and Areny groups being almost negligible. Apart from those structures associated with the layer-parallel ~~shearing~~slipping, the few additional deformation structures point out for a maximum stress oriented at low angle to bedding.

During the late stage of folding instead, when the unconformity angle exceeded 120-130°, the maximum stress was south-dipping, with an angle higher than 30°. The stress attained a state allowing ~~shearing~~slipping, as faulting in the Vallcarga started. Contextually, bedding surfaces of the Vallcarga continued to be sheared, while shearing along the unconformity (in the central limb) arrested.

6.3 Flexural-slipping and stress reorientation

The information discussed above ~~evidences~~argues for a syn-folding maximum stress rotation/reorientation within the growing anticline, from sub-horizontal early-folding layer-parallel shortening in Tavani et al (2011) to south-dipping maximum stress in overturned strata documented here. As schematically illustrated in figure 7d, we infer that the sub-horizontal maximum stress applied to the leading syncline of the growing Sant Corneli-Bóixols Anticline (i.e. the remote applied stress has an andersonian compressive configuration; Anderson, 1951), progressively rotated as it was transmitted across folding rock volumes affected by widespread flexural-slipping. In agreement with what illustrated in the introduction, here this process of stress deflection is interpreted as associable with the flexural-slipping mechanism. In fact, as largely documented, ~~shearing~~slipping along low-friction faults produces the perturbation of the remotely applied stress field (e.g. Pollard and Segall, 1987; Soliva et al., 2010) and, in particular, reduction of the fault-parallel shear stress component causes the orientation of principal stress to rotate locally towards a fault-parallel direction. Consistently with this, the coupling between flexural-slip and maximum stress reorientation documented in other structures, has been attributed to the fact that slipping along closely spaced low friction bedding surface imposes the maximum stress to orient at low angle to the slipping bedding surface in a wide area (i.e. the flexural-slip folded area), as mentioned in the introduction (Wiltschko et al., 1985; Ohlmacher and Aydin, 1997; Tavani et al. 2012). This concept fully applies to the data presented in this work until the strata attained a strongly overturned attitude. The close link between flexural-slipping and stress reorientation also implies that the amount of deflection of the maximum compressive stress scales with the amount of flexural-slipping. Accordingly, if the growth of an anticline occurs in a discontinuous fashion, the orientation of maximum compressive stress is expected to rotate repeatedly during the repeated pulses of flexural slip. In the case documented here, the absence of any indicators of a sub-horizontal maximum stress could be related to the fact that andersonian stress configuration would characterise stages in which the maximum stress is low and in a sub-critical state, not allowing faulting and folding. Repeated pulses of maximum stress increase would instead cause the progressive slipping of bedding surfaces, with the consequent maximum stress deflection.

Conclusions

The key questions in this study were to constrain up to the range of dip values over which the flexural slip mechanism can operate.. This fundamental information allows to discriminate whether flexural-slipping is a nearly passive process with respect to the stress field evolution (i.e. the remotely applied stress is only locally deflected) or rather, it is a fully active process, discontinuous at the local scale but sufficiently dense in time and space at the scale of the fold, able to reorient the remotely applied stress field. The answer is that flexural-slip in the studied structures was an active process. It operated up to 120° of dip and caused the maximum stress to progressively reorient at low angle to bedding until strata attained an overturned attitude.

Acknowledgments

The authors sincerely thanks the reviewers, Ryan Shackleton, Richard Lisle, and Juliet Crider, and the editors, for their constructive comments and suggestions. All the structural data and the photographs presented in this work can be obtained from the corresponding author. The cross sections presented in this work have been constructed using the 3D Move software. This work is a contribution of the Institut de Recerca Geomodels and the Geodinàmica i Analisi de Conques research group (2014SGR467SGR) from the Agència de Gestió d'Ajuts Universitaris i de Recerca (AGAUR) and the Secretaria d'Universitats i Recerca del Departament d'Economia i Coneixement de la Generalitat de Catalunya. Move restoration software was used for cross-section construction.

Captions

Figure 1

(A) Geological maps of eastern Pyrenees, with detail of the Sant Corneli-Bóixols Anticline. Geological map (B) and schematic cross-section (C) of the study area, with cumulative contouring of poles to bedding and best-fit beta axis of syn-folding beds, and poles of pre-folding beds (red circles). (D) Panoramic view of the study area, with insets showing the location of figures 2 to 4 and the photographed area in cross-section and map-view, respectively.

Figure 2

Structures exposed at the northern limb of the San Maximí Syncline. (A) Cross-sectional location of the site. (B) South-dipping conglomerates of the Areny Group unconformably overlying the overturned north-dipping strata of the Vallcarga Group, with stereoplots of the unconformity and bedding surfaces in the Vallcarga Group. (C) Detail of the unconformity, showing S-C-C' fabric, with corresponding stereoplots. (D) South-dipping alternating conglomerates and siltstones of the Areny Group, with pervasive cleavage at high angle to bedding.

Figure 3

Transitional area between the San Maximí Syncline and the Remolina Anticline. (A) Cross-sectional location of the site. (B) Shallow-dipping unconformity between the Areny and the Vallcarga groups reactivated as a low-angle fault and displaced by a high-angle fault. Details of the low- and high-dipping faults are shown, together with stereoplots of faults and bedding surfaces of the Vallcarga Group. (C) Panoramic view and stereoplot of a near vertical fault system uplifting the

Remolina Anticline, which has folded strata of the Areny Group unconformably on top of near vertical strata of the Vallcarga Group.

Figure 4

Macro- and meso-structures of the Remolina Anticline. (A) Panoramic view and line-drawing of the Remolina Anticline (with insets showing the location of figure 4B and C, and figure 5B), with stereoplots of faults and bedding measured in the Vallcarga Group. (B) Detail of a south-dipping reverse fault having in its footwall sub-horizontal carbonates of the Areny Group on top of overturned strata of the Vallcarga Group. Stereoplots show fault data in the Areny carbonates. (C) Details of the unconformity, with S-C-C' illustrated and plotted.

Figure 5

(A) Panoramic view of the hinge zone of the Remolina anticline, visible in the Areny strata that are on top of constantly-dipping strata of the Vallcarga Group. (B) Detail of the unconformity between Areny and Vallcarga groups at the southern limb of the anticline, where no evidence of shear occurs. (C) Detail of slickenlines along a near vertical bedding surface of the Areny strata, providing a top to the north ~~shear~~slip sense for the upper bed. (D) Stereoplots of bedding surfaces and faults collected in the Areny Group strata of the southern limb of the Remolina Anticline.

Figure 6

(A) Evolving angular relationships between unconformable sequences during flexural-folding in the inner limb of a syncline, with incremental ~~shear~~slip senses along pre-unconformity layers and along the unconformity indicated, for different initial unconformity angles. The position of six ~~key-~~points undergoing folding is illustrated, as well as the dip of pre-unconformity layers (*D*) and of the unconformity angle (*U*), which is the angle between the unconformity and the underlying layers. (B) X and Y coordinates of the six points of figure 6a, with length of segments, and derived amount of ~~shear~~slip along the unconformity (ΔS) and unconformity angle (U). (C) Graphical solution of equations in figure 6b. Blue lines relate the unconformity angle (*U*) to the dip of pre growth strata (*D*) for different initial unconformity angle (U_0). Red lines relates the normalised ~~shear~~slip along the unconformity in the inner portion (i.e. $\Delta S = P_4P_5$ segment divided *H*) to *D*, for different initial unconformity angle (U_0). Notice that the Y axis for red lines is on the right and that positive and negative values are flipped. The lines indicate the cumulative ~~shear~~slip along the unconformity, while the grey area bordered by the black line, indicate the area where the incremental ~~shear~~slip is negative.

Figure 7

(A) Scheme showing the present day geometry of the frontal limb of the Sant Corneli-Bóixols Anticline. (B) Details showing the structural assemblages observed at the Remolina Anticline, with two alternative configurations for the maximum stress orientation. The maximum stress forms the following clockwise angles: $d\sigma_1$ with the horizontal, γ with the unconformity, α with the bedding-parallel steps of flexural-slip faults in the Vallcarga Group, β with the oblique to bedding strands of the flexural-slip fault in the Vallcarga Group. Red and cyan colours indicate angles not compatible and compatible with the observed ~~shear~~slip pattern, respectively. (C) Relationships between $d\sigma_1$, and α, β, and γ, with the red area indicating the orientation of the maximum stress not compatible with the ~~shear~~slip pattern observed at the Remolina Anticline. (D) Inferred maximum stress trajectories during the late stages of folding.

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