RESPONSE TO REVIEWERS

Reviewer 1

Comment 1
it [the ms.] still suffer some important points that needs to be adressed. 1) The first one is that the overall interpretation seems heavily model driven. Indeed the E-W fractures are interpreted as forebulge-parallel extension, which make sense, but the systematic attribution of the N-S fractures to accros strike extension can be argued against: - an alternate interpretation would be to consider the N-S fractures as related to LPS, postponing the E-W, forebulge related fractures, leading to similar patterns than the one described.
Response: Done.
We thank the reviewer for this comment. We have added this text:
“LPS is to be excluded, as the state of stress in this case would include a positive minimum stress (Fig. 1). In agreement, LPS-related extensional structures can form only due to fluid pressure contribution and they include mm- to cm-long fractures filled with calcite (which is removed from pressure solution seams, Fig. 1; Tavani et al., 2015 and references therein). The type (joints with no calcite infill) and size (tens of m-long) of transverse extensional structures described here are incompatible with the layer-parallel shortening mechanism.

Comment 2
The occurence of a NNESSW (what is the mean strike of it?) goes well into this alternate scenario, as the Ebro Basin underwent a regional 20◦ Clockwise rotation during paleogene, as reconstructed by the paleomagnetic data (Parès et al., 1988, Physics of the Earth and Planetary Interiors, Volume 52, Issue 3-4, p. 267-282). This rotation does not seem to have been considered by the authors, and I think this needs adressed.
Response: Not agreed.
It has been recently demonstrated (after the initial papers describing paleomagnetic data in the Triassic red beds) that the Ebro basin has not experienced a general rotation during the Paleogene. Paleogene vertical-axis rotations in the Pyrenees are mainly related with displacement gradients of the thrust sheets, mostly resulting from the distribution of the Triassic salt detachment horizon (Sussman et al., 20014; Soto et al., 2006; Muñoz et al., 2013). In addition, older vertical axis rotations, can be related with the extensional and sinistral displacement of Iberia during Early Cretaceous (Dinarès-Turell and García-Senz, 2000; Gong et al., 2009).
Apart from these vertical axis rotations, which are at present well documented, the Ebro basin and in detailed the eastern part of the Ebro basin where this is study has been located has not experienced any vertical-axis rotation as documented by paleomagnetic studies (Burbank et al., 1992; Taberner et al., 1999).

Burbank, D. W., Puigdefàbregas, C., & Muñoz, J. A. (1992). The chronology of the Eocene tectonic and stratigraphic development of the eastern Pyrenean foreland basin, northeast Spain. Geological Society of America Bulletin, 104(9), 1101–1120. http://doi.org/10.1130/0016-7606(1992)104<1101:TCOTET>2.3.CO;2

Dinarès-Turell, J., & Senz, J. G. (2000). Remagnetization of Lower Cretaceous limestones from the southern Pyrenees and relation to the Iberian plate geodynamic evolution. Journal of Geophysical Research: Solid Earth (1978–2012), 105(B8), 19405–19418. http://doi.org/10.1029/2000JB900136

Gong, Z., van Hinsbergen, D. J. J., Vissers, R. L. M., & Dekkers, M. J. (2009). Early Cretaceous syn-rotational extension in the Organyà basin—New constraints on the palinspastic position of Iberia during its rotation. Tectonophysics, 473(3-4), 312–323. http://doi.org/10.1016/j.tecto.2009.03.003

Soto, R., Casas-Sainz, A. M., & Pueyo, E. L. (2006). Along-strike variation of orogenic wedges associated with vertical axis rotations. Journal of Geophysical Research: Solid Earth, 111(B10), B10402. http://doi.org/10.1029/2005JB004201

Sussman, A. J., Butler, R. F., Dinarès-Turell, J., & Vergés, J. (2004). Vertical-axis rotation of a foreland fold and implications for orogenic curvature: an example from the Southern Pyrenees, Spain. Earth and Planetary Science Letters, 218(3-4), 435–449. http://doi.org/10.1016/S0012-821X(03)00644-7

Taberner, C., Dinarès-Turell, J., Giménez, J., & Docherty, C. (1999). Basin infill architecture and evolution from magnetostratigraphic cross-basin correlations in the southeastern Pyrenean foreland basin. Geological Society of America Bulletin, 111(8), 1155.

Comment 3
Two important things are missing to back up the interpretation of the authors: relative chronology; and observation and report of systematic occurence of N-S joints with E-W joints.
Response: Done
The few E-W striking joints systematically abut on the N-S striking set, indicating that E-W striking joints are cross-joints formed perpendicular to the master (N-S) joint set. This is well shown in figures 2D and 2E (for the NNW-SSE striking set), and it is now mentioned in the revised text.

Comment 4
I would be interested to see reported the length of the fracture tracks for each set, I am sure it could be of interest as well to solve the problem I mentionned in my first comment.
Response: Done
Graph added in figure 3f

There is also minor remarks:
Comment 5
Page 2, line 26-27:"Even in arched systems, the forebulge, the foredeep, and the belt tend to be nearly parallel to each other locally" –> can you report related references?
Response: Done
Added

Comment 6
Page 4, line 28-29: "The NE and SE portions of the study area are highly vegetated (Fig. 3d,e) and only a few joint traces have been mapped there." –> how does it affect the statistic? Why not leaving these out?
Response: Done
We agree. Nodes with < 20 data have not been considered in our analysis. This is now mentioned in the text.

Comment 7
Page 5: Why did you choose these lenghts for the triangular mesh? Do you need it to be one order of magnitude longer than the longest fractures? Can you discuss the impact?
Response: Done
The radius of the circular moving window is set to these values for these two reasons: 1) it is two orders of magnitude longer than the average length of joints; 2) it is larger enough to ensure that at each node the data number is >20. This is now explicated in the text

Comment 8

Figure 2 C-F: The north is not really clear from this representation.
Response: Done
North added.

Reviewer 2

Comment 1
In the introduction, you outline a mechanism to explain transverse jointing in the foreland. Then you continue with the outlook that the acquired remote sensing data allows to investigate the primary mechanism for this joint formation. Hence I wonder: Haven't you proposed already before the data collection and discussion of what the primary mechanism is? Does this lead to a bias in the data interpretation? Maybe it would be better to present the model after the data presentation in the discussion to avoid that such an impression might arise.

Response: Not agreed.
This is a matter of writing style and not a source of bias. In our view the rationale of the work and the state of the art must include a brief introduction to the causative geological processes allowing to understand data.

Comment 2
Also on that regard, a discussion on the potential driving force behind the suggested orogen-parallel stretching of the foreland basin is largely missing (or well hidden, in case I missed it), which would be very interesting though.
Response: Done
We have added this text in the discussion: *The basic concept behind this mechanism is the following: when a straight line joining two fixed points - the tips of a fault in the case of Destro (1995) or the edges of the foredeep in the case of Quintà and Tavani (2012) – becomes an arch, there is stretching (Fig. 1b), which causes extensional stress parallel to the direction of elongation. In essence, this mechanism is expected to operate in any doubly plunging foredeep, particularly at its lateral edges, such as in the study area (Fig. 3a)*

Comment 3
In the introduction, it is briefly referred to two publications invoking the possibility of lithospheric bending to account for such kind of stretching (Doglioni, 1995; Quintà and Tavani, 2012; although the process described by Doglioni is regarded as not applicable for the study area, which is comprehensible). In the discussion, this subject is covered with only two sentences (page 7 line 31 to page 8 line 3; half of it being a repetition of the introduction statement). Here, foreland-parallel stretching is suggested to form the N-S joints and an analogue reference is made to the process of release faulting (Destro, 1995). I think this requires much more attention: Destro (1995) describes a purely extensional setting and it is therefore not straightforward to understand how this applies to the Pyrenean foreland, especially in the light that you propose foreland-parallel extension from the Paleocene until the end of convergence (page 7, line 22). Hence, I believe a more elaborate discussion for the use of this model is necessary, in particular, and potential driving mechanism for such stretching, in general.
Response: Done
See response to the previous point.

Comment 4
Adding to this, you mention the westward plunge of the foredeep basin and refer to figure 3a. I am not sure if this is it actually visible in the figure or if it requires previous knowledge of the region to identify it!? I think an E-W cross-section would be very helpful.
Response: Done

We have added the trace of the axis of the foredeep basin in figure 3 to show its W-ward plunge.

Comment 5
A second issue revolves around the timing of joint formation. You state that the dominant N-S trending joint system formed prior to folding and refer to figure 2b, where joints are supposedly tilted. Unfortunately, from the picture alone, it is very hard to see this. How did you determine that these joints are tilted? How can you exclude the possibility of joint formation after folding? Such a determination appears to me as a very difficult asset, since you would have to know their original orientation and at the same time line out why its present orientation is not the original one. I think this is a very important issue that needs to be clarified.
Response: Done
Timing of deformation is rather evident from figure 2. We have improved the description of this figure: *In the field, joints are constantly bedding-perpendicular, regardless of the bedding dip (Fig. 2a,b), and they are characterized by the occurrence of either a single set (Fig. 2c) or by a ladder pattern (Fig. 2d,e). In the latter case, the few E-W striking joints are almost everywhere perpendicular to the N-S striking set and abut on it (Fig. 2e). This indicates that E-W striking joints are cross-joints formed perpendicular to, and about synchronously with, the N-S striking joint set*

Comment 6
A second argument for the age of joints is their absence in Quaternary sediments. First, there is still a large age span from the Quaternary to the Eocene (using the word "evidence" (page 7, line 9) for an Eocene formation age is therefore maybe a stretch), and second: what is the character of these sediments? Are they solidified to a degree where fractures would be able to form in case the joints in the Eocene rock were of Quaternary age?
Response: Done
See response to previous point.

Comment 7
Another thing: As you have been in the field, it would be great to see a comparison of field data with the remote lineament data. E.g. do the joints have a preferential dip direction, are they all just vertical?
Response: Done
We have added stereoplots of joints collected in the northern portion of the study area.

Comment 8
Figure 1: This is a very nice figure, but some features can only be identified when zooming in a lot, i.e. the text "peripheral bulge", veins, and stylolites. Please improve this. Also, I recommend to place the names forebulge, foredeep, foreland fold-andthrust belt into/above the block figure and not just mention them in the figure caption.
Response: Done
Labels added.

Comment 9
Figure 2:
1) please show the locations of these outcrops in figure 3.
2) Also, I would prefer to show field photos after showing a map of the study area.
3) In Figure 2b, please point at the joints as it is not super clear that the big surface is, I assume, the bedding surface.
Response: Partly agreed
1) This cannot be done due to the size of the figure: the labels of the five sites would cover much of the figure.
2) In the text the figure 2 is called before figure 3, so it cannot be shown before.

3) Yes, the south-dipping surface is the bedding, this is now mentioned.

Comment 10
Figure 3: add some placemarks (e.g. towns) to the map, so that it's a bit easier for the reader to capture the location of the study area. (took me a little bit to find the exact area on google earth).
Response. Done.
Added

Comment 11
Figure 5: I think it would be really nice, if you exemplarily show a few rose plots (joint length-weighted) for different colored regions in figure 5. I believe this would make it much easier for the reader to understand how to read the color code of the figure.
Response: Done
This is probably a misunderstanding. The colour code refers to the dispersion of azimuthal data, which is not well appreciable in rose diagrams as the dominant set is much developed than the other sets. We have improved the caption of the figure.

Transverse jointing in foreland fold-and-thrust belts: a remote sensing analysis in the eastern Pyrenees

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Abstract

Joint systems in the eastern portion of the Ebro Basin of the eastern Pyrenees enjoy near continuous exposure from the frontal portion of the belt up to the external portion of its associated foredeep. Utilizing orthophoto mosaics of these world class exposures, we have manually digitized over 30000 joints within a 16x50 km study area. The mapped traces exhibit orientations that are dominantly perpendicular to the trend of the belt (transverse) and, subordinately, ~~orthogonal~~parallel to ~~it~~the belt (longitudinal). In particular, joints systematically orient perpendicular to the trend of the belt both in the frontal folds and in the inner and central portion of the foredeep basin. Longitudinal joints occur rarely, with a disordered spatial distribution, exhibiting null difference in abundance between the belt and the foredeep. Joint orientations in the external portion of the foredeep become less clustered, with adjacent areas dominated by either transverse or oblique joints. Our data indicates that joints in the studied area formed in the foredeep in response to a foredeep-parallel stretching, which becomes progressively less intense within the external portion of the foredeep. There, the minimum stress direction becomes more variable, evidencing poor contribution of the forebulge-perpendicular stretching on stress organization.

Introduction

Fractures can be effective pathways for fluid flow (e.g. Laubach et al., 2019), thus impacting production of hydrocarbons (Barr et al., 2007; Engelder et al., 2009; Questiaux et al., 2010) and geothermal water (Haffen et al., 2013; Vidal et al., 2017), the pathways and fates of contaminants released from deep geological radioactive waste repositories (Berkowitz et al., 1988; Iding and Ringrose, 2010) and the sustainable management of groundwater (Masciopinto and Palmiotta, 2013). Associated with crustal tension, joints are ubiquitous open-mode fractures occurring in a range of tectonic settings, including collisional belts. In collisional settings, layer bending and stretching during the growth of thrust-related anticlines has conventionally been invoked as the principal causative process for the development of joints oriented approximately parallel (e.g. Ramsay, 1967; Murray, 1968) and perpendicular (e.g. Dietrich, 1989; Lemiszki et al., 1994) to the trend of the belt and of the thrust related anticlines. However, the frequently observed obliquity between joints (and other meso-scale structures) and the trend of the hosting anticlines (e.g. Tavani et al., 2019; Beaudoin et al., 2020), along with the documented occurrence of joints in exposed forelands (e.g. Dunne and North, 1990; Zhao and Jacobi, 1997; Billi and Salvini, 2003; Whitaker and Engelder, 2006), has more recently led to the conclusion that, in many cases, joints and other kinds of extensional fractures exposed in thrust and fold belts have developed prior to folding and thrusting, within the foreland region (e.g. Doglioni, 1995; Zhao and Jacobi, 1997; Tavarnelli and Peacock, 1999; Lash and Engelder, 2007; Branellec et al., 2015; Basa et al., 2019; Giuffrida et al., 2019; Martinelli et al., 2019; Carrillo et al., 2020), where joints are layer-perpendicular and commonly oriented parallel (longitudinal) and perpendicular (transverse) to the belt-foredeep-forebulge trend (Tavani et al., 2015).

A partially unresolved question in foreland deformation relates to the development of transverse joints, which requires a tensile minimum stress oriented parallel to the foredeep. Even in arched systems, the forebulge, the foredeep, and the belt tend to be nearly parallel to each other locally (e.g. the Hellenic arc, the Apennines-Calabrian arc, the Betic-Rif arc). The shortening direction in the inner portion of the foredeep (subjected to layer parallel shortening) and the stretching direction in the forebulge (where bulge-perpendicular stretching induced by lithospheric outer arc extension operates) are nearly parallel in a belt-perpendicular transect (Fig. 1). In addition, in the innermost portion of the foredeep, where layer parallel shortening operates, the σ2 is typically vertical and the σ3 is positive,

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horizontal, and parallel to the trend of the belt (Tavani et al., 2015). Given the above, there should be an area in between the inner portion of the foredeep and the peripheral bulge where σ1 becomes vertical and where σ3 is still horizontal and parallel to the belt (Fig. 1a). This scenario could explain the development of layer-perpendicular transverse extensional structures, with transverse extensional faults or veins expected to develop where σ3 is positive. In this scenario, transverse joints occurring in this zone of localized tension could only develop as cross-joints (e.g. Gross, 1993) of the longitudinal set formed in the forebulge. This simplified model does not explain the documented occurrence of transverse joints in areas where longitudinal joints do not occur or represent the cross-joint set (e.g. Zhao and Jacobi, 1997; Quintà and Tavani, 2012). This framework does not admit a simple stress permutation in the foredeep and requires a negative σ3 connected to a foredeep-parallel stretching component (Fig. 1b). Lithospheric bending of the foredeep, both along the horizontal plane (e.g. Doglioni, 1995) and along the vertical plane parallel to the trench (Quintà and Tavani, 2012), has been invoked as a process able to produce foredeep-parallel stretching.

Continuous exposures across the entire foreland region of the eastern Pyrenees allows investigation of the primary mechanism responsible for transverse joint development described above. Tens to hundreds of meters long joints affect the sedimentary sequence of the Ebro foredeep basin (Fig. 2a), and are found tilted within the frontal structures of the Pyrenean belt (Fig. 2b). These pre-folding joints are exceptionally exposed and mappable from orthophotos (Fig. 2c-f), from which they can be traced almost continuously from the external portion of the foredeep until the thrust belt. We have remotely mapped 30059 joints traces from the aforementioned orthophoto dataset and obtained their azimuthal distributions across the study area. Subsequently, this extended lineament database has been used to constrain the causative mechanism behind transverse jointing in the Ebro foredeep basin.

Geological ~~Setting~~framework

The study area is situated in the eastern Ebro foreland basin within an area connecting the eastern Pyrenees with the Catalan Coastal Ranges (Fig. 3a). The Pyrenees is an EW-striking orogenic system that formed as the Iberian and European plates collided from Late Cretaceous to Miocene times (Roest and Srivastava, 1991; Rosenbaum et al., 2002; Muñoz, 1992, 2002), and constitutes an asymmetric, doubly vergent orogenic wedge above the northward subduction of the Iberian lithosphere beneath the European plate (Chevrot et al., 2018). As a result, the Ebro basin formed as a flexural foreland developed on the downgoing Iberian plate at the southern margin of the chain (Beaumont et al., 2000). In the study area, to the south of the Ebro Basin (Fig. 3a), the Catalan Coastal Ranges developed as a Paleogene intraplate left-lateral transpressional system (López-Blanco, 2002; Santanach et al., 2011). The low-displacement character of thrusts and the absence of an associated foredeep both evidence the limited importance of this range. A series of NE-SW and NW-SE trending extensional faults strike parallel and perpendicular to the Catalan Coastal Range respectively, which are a result of the late Oligocene-Miocene opening of the NW Mediterranean basin (Vegas, 1992; Sàbat et al., 1995; Granado et al., 2016a).

The study area where joint traces have been digitized is delimited to the north by the frontal Pyrenean thrusts and by the Eocene Bellmunt anticline (Figs. 3a,b). This anticline comprises the Paleocene to upper Eocene foredeep infill. Immediately to the south of the anticline (i.e.< 5 km), this multilayer becomes sub-horizontal and thins southward where the Paleozoic to Mesozoic foredeep floor gently rises up ~~southward~~ and becomes exposed (Fig. 3a). There, this <u>pre-orogenic</u>~~Paleozoic to Cenozoic~~ succession is slightly tilted to the north by uplift in the footwall of NW-SE striking ~~L~~<u>l</u>ate Oligocene to Neogene extensional faults. Further to the southwest, this succession is affected by the Paleogene contractional structures of the Catalan Coastal Ranges (Fig. 3b).

<u>In the field, joints are constantly bedding-perpendicular, regardless of the bedding dip (Fig. 2a,b), and they are characterized by the occurrence of either a single set (Fig. 2c) or by a ladder pattern (Fig. 2d,e). In the latter case, the few E-W striking joints are almost everywhere perpendicular to the N-S striking set and abut on it (Fig. 2e). This indicates that E-W striking joints are cross-joints formed perpendicular to, and about synchronously with, the N-S striking joint set.</u>

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Data and Methods

Joints have been digitized within the 16.4x49.2 km area displayed ~~i~~<u>o</u>n Figure 3, on 25 and 50 cm/px orthophotos provided by the Spanish Instituto ~~Geografico~~ <u>Geográfico</u> Nacional via the PNOA (Plan Nacional de Ortofotografía Aérea) project (https://pnoa.ign.es/). The open source geographical information system QGIS 3.4 has been used to manually digitize 30059 joint traces. A collection of these traces seen on orthophotos is provided in Figure 2c-f. Joints have been digitized in Bartonian and, subordinately, in Lutetian and Priabonian sedimentary rocks (Fig. 3c). The NE and SE portions of the study area are highly vegetated (Fig. 3d,e) and only a few joint traces have been mapped there. Quaternary sediments unaffected by joints crop out in the central portion of the study area (Fig. 3d).

Digitized traces have lengths ranging from 2 to 100 m, with an average of ~20 m (Fig. 3f). The frequency distribution of trace trend shows that the vast majority of the mapped joints are approximately N-S striking (Fig. 3f). A second subordinate set corresponds to E-W striking joints, which in the field occur as cross-joints (Fig. 2d). The frequency distribution of trace trend is not symmetrical around these orthogonal sets, due to the presence of a third less abundant set composed of NW-SE oriented joints (Fig. 2e,f). The NW-SE striking joints are mostly seen in the southern portion of the study area, in exposures where the N-S striking set is not occurring. ~~Generally speaking, as previously~~As mentioned above, exposures are ~~mostly~~frequently characterized by a single set (Fig. ~~3~~2c,d). At ~~a few~~many locations, the dominant set is accompanied by associated cross-joints (Fig. 2~~3~~d). Very rarely, two mutually oblique sets occur in the same exposure (Fig. 2f).

In order to evaluate the variability of joint traces, the 16.4x49.2 km study area has been divided into meshes of equilateral triangular elements with edge lengths of 1025m (Mesh 1) and 1640m (Mesh 2). At each node, mean value and variance of trace trends has been computed using a circular moving window with a radius of 1200m (Mesh 1) and 1900m (Mesh 2). The radius of the circular moving window is set to these values for two reasons: 1) it is two orders of magnitude longer than the average length of joints; 2) it is large enough to ensure that most of the nodes have data number >20, as only nodes with data number > 20 have been analyzed. Since trace trends are circular data with an angle (α) over a period (π,) in agreement with Mardia (1975) we used equations 1 to 4 to derive at each node the circular mean value (Mv_π), the circular variance (V_π) and the resultant length (R_π; $V_\pi = 1-R_\pi$), the latter spanning from 0 (unclustered distribution) to 1 (perfectly clustered distribution). In the presence of cross-orthogonal joint sets, it is also useful using a period of $\pi/2$, thus modifying Mardia's equations and introducing the $Mv_{\pi/2}$ and $R_{\pi/2}$ parameters, which are computed using Equations 5 to 8.

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Comment 7

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$$C_{\pi}=\frac{\sum_{i=1}^{n}\cos(2\alpha_i)}{n}\ (1);\ S_{\pi}=\frac{\sum_{i=1}^{n}\sin(2\alpha_i)}{n}\ (2);\ V_{\pi}=1-R_{\pi}=1-\sqrt{C_{\pi}^2+S_{\pi}^2}\ (3);\ Mv_{\pi}=\frac{Arctan\left(S_{\pi}/C_{\pi}\right)}{2}\ (4)$$

$$C_{\pi/2}=\frac{\sum_{i=1}^{n}\cos(4\alpha_i)}{n}\ (5);\ S_{\pi/2}=\frac{\sum_{i=1}^{n}\sin(4\alpha_i)}{n}\ (6);\ V_{\pi/2}=1-R_{\pi/2}=1-\sqrt{C_{\pi/2}^2+S_{\pi/2}^2}\ (7);\ Mv_{\pi/2}=\frac{Arctan\left(S_{\pi/2}/C_{\pi/2}\right)}{4}\ (8)$$

By using these four parameters together, instead for example of the classical k-means clustering analysis, it is possible to derive important considerations on the distribution of polymodal distributions in which two mutually orthogonal sets do occur, as illustrated in Figure 4. We compare the Mv and the R parameters computed using the π and $\pi/2$ periods. In the first example two parallel traces are analyzed, resulting in $Mv_{\pi/2} = Mv_{\pi}$, and $R_{\pi/2} = R_{\pi} = 1$ (i.e. circular variance = 0). When data dispersion is slightly increased (Example 2), $Mv_{\pi/2}$ is still equal to Mv_{π}, whereas $R_{\pi/2}$ decreases faster than R_{π}. Further increase of data dispersion (Example 3), in an asymmetric distribution (i.e. non-orthogonal sets), causes additional decrease of $R_{\pi/2}$ with respect to R_{π}, and slight divergence between $Mv_{\pi/2}$ and Mv_{π}. In the presence of a cross-orthogonal subset, the statistical usefulness of $R_{\pi/2}$ becomes evident, as illustrated in Example 4. In this case, R_{π} rapidly approaches zero, suggesting high dispersion (i.e. unrepresentative Mv_{π}), whereas $R_{\pi/2}$ is essentially unaffected with respect to Example 2, indicating low- dispersion and a representative $Mv_{\pi/2}$. However, the use of the $\pi/2$ period only returns results in the 0 to $\pi/2$ range, so that NW-SE trending traces result in a NE-SW trending mean value ($Mv_{\pi/2}$), as shown in the Example 5. In summary, Mv_{π} is useful to derive the mean direction, whereas $R_{\pi/2}$ and R_{π} should be used in conjunction to discriminate between populations in which oblique sets occur ($R_{\pi/2} < R_{\pi}$) from those in which two perpendicular sets occur ($R_{\pi/2} > R_{\pi}$).

Results

Figure 5 displays attribute maps generated from Mesh 1 and Mesh 2 using the trace orientation parameters described above. Both Mesh 1 and Mesh 2 have $R_{\pi} > 0.5$ across almost the entire~~ty of the~~ study area, with the only exception being in ~~the~~ its NW corner~~ of the study area~~. For $R_{\pi/2}$, in addition to the NW corner, the central portion of the study area has $R_{\pi/2} < 0.5$. Noteworthy differences between R_{π} and $R_{\pi/2}$ occur: (1) in the NW corner ($R_{\pi} \ll R_{\pi/2}$) and (2) in the central area ($R_{\pi} \gg R_{\pi/2}$). The first area corresponds to a vegetated folded and faulted ~~area~~ zone (Fig 3b-e). Consequently, we consider the dataset poorly reliable in this location. In the central portion of the study area, the difference between R_{π} and $R_{\pi/2}$ (which increases as data dispersion increases) is less pronounced in Mesh 1 than Mesh 2. Thus, data dispersion increases with increasing the search window size (1200m for Mesh 1 and 1900m for Mesh 2), evidencing that joint orientation is changing in this area. In the rest of the analyzed foreland, $R_{\pi/2}$ has values similar to R_π, indicating approximately unimodal data distribution within this region, and poor spatial organization of the longitudinal cross-joints.

Distribution of Mv_π relates to the prevalence of NS-striking joints in the northern and central portion of the study area. Towards the south, patches characterized by both N-S and NW-SE-striking joints occur. High values of R_π and $R_{\pi/2}$ are characteristic of such subareas, which as previously mentioned, is indicative of unimodal joint trace distributions.

Discussion

Remotely sensed and mapped joint traces in the eastern portion of the Pyrenees-Ebro system show systematic distributions of azimuthal orientations. In the frontal portion of the belt and within the foredeep, joints are mostly transverse (i.e. N-S-striking), with limited occurrence of E-W-striking longitudinal cross-joints. Approaching the southern border of the foredeep, joints exhibit both N-S and NW-SE orientations where the pre-Cenozoic floor of the foredeep is exposed. Joints affect the Lutetian to Priabonian foredeep infill, and are found tilted together with strata within the Bellmunt anticline (Fig. 2b), which is Priabonian in age (Burbank et al., 1992). Given the above, ~~the timing of~~ jointing ~~in the area~~ must have taken place ~~be~~ during or before the Priabonian. ~~Evidencing this proposed framework, there are no systematic and pervasive joints affecting Quaternary sediments (Fig. 3), while Oligo-Mio-Pliocene sediments are not present in the rock record of the studied area.~~ The occurrence of the N-S striking joints within the Ebro foredeep is documented also to the west of the study area (e.g. Turner and Hancock, 1990), where joint emplacement affects up to the Miocene (Arlegui and Simon, 2001). Transverse joints, striking approximately NNE-SSW occur also to the SW in ~~the~~ Bartonian to Priabonian strata cropping out at the boundary between the Ebro basin and the Catalan Coastal Ranges (Alsaker et al., 1996). These data indicate that transverse joints systematically developed in the foredeep basin of the E-W oriented Pyrenean belt. Locally, the process of transverse jointing occurred until the early Miocene (i.e. until the end of mountain building). Also, pre-thrusting transverse extensional faults of upper Paleocene to lower Eocene age occur a few tens of km to the NE of the study area (Carrillo et al., 2020), being presently incorporated into the Pyrenean belt. Thus, we conclude that foredeep-parallel extension has occurred in the foredeep of the Pyrenean belt since the Paleocene and until the end of convergence. Transverse joints documented in this work clearly represent foredeep-related structures, which can develop by (i) N-S oriented layer-parallel shortening (LPS) or (ii) E-W oriented along foredeep stretching –(Tavani et al., 2015). LPS is to be excluded, as the state of stress in this case would include a positive minimum stress (Fig. 1). In agreement, LPS-related extensional structures can form only due to fluid pressure contribution and they include mm- to cm-long fractures filled with calcite (which is removed from pressure solution seams, Fig. 1; Tavani et al., 2015 and references therein). The type (joints with no calcite infill) and size (tens of m-long) of transverse extensional structures described here are incompatible with the layer-parallel shortening mechanism. –

The relatively constant orientation of joints along the strike of the foredeep, the occurrence of appreciable dispersion at the outer border of the foredeep, and the remarkably poor abundance of longitudinal joints allow us to derive two major conclusions:

(1) The almost linear trend of the eastern Pyrenees facilitates the exclusion of planar arching (e.g. Doglioni, 1995; Zhao and Jacobi, 1997) as the causative process for generating foredeep-parallel stretching (i.e. required to establish the negative σ3 responsible for transverse jointing). Arching along the vertical plane parallel to the trench (Quintà and Tavani, 2012) represents instead a viable mechanism for generating along-foredeep stretching. This is analogous, albeit at a larger scale to the process of release faulting described by Destro (1995). The basic concept behind this mechanism is the following: when a straight line joining two fixed points - the tips of a fault in the case of Destro (1995) or the edges of the foredeep in the case of Quintà and Tavani (2012) – becomes an arch, there is stretching (Fig. 1b), which causes extensional stress parallel to the direction of elongation. In essence, this mechanism is expected to operate in any doubly plunging foredeep, particularly at its lateral edges, and requires a laterally decreasing depth of the foredeep, which is confirmed by the westward plunge of the foredeep basin-, such as in the study area (Fig. 3a).

(2) Extension in the peripheral bulge, which is documented from many active and fossil foredeep basins (e.g. Bradley and Kidd, 1991; Ranero et al., 2003; Tavani et al., 2015; Granado et al., 2016b), including the lower Eocene foredeep basin presently incorporated into the Pyrenees (e.g. Martinez et al., 1989; Pujadas et al., 1989) appears to be weakly influential at the southern border of the study area (i.e. the upper Eocene peripheral bulge). Indeed, the

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observed longitudinal joints are characteristically subordered, forming locally as cross-joints to the identified transverse set within the study area (Fig. 2d). The transverse set becomes less organized at the southern margin of the foredeep, where patches of N-S and NW-SE dominated domains do occur. This evidences the absence of a major forebulge-perpendicular extension capable of systematically reorienting σ3 at the external foredeep edge.

Conclusions

Analysis of remotely sensed and mapped joints in the eastern Pyrenees and in the adjacent Ebro foreland basin indicates that the emplacement of the dominant joint set within the area, which strikes perpendicular to the trend of the foredeep occurred prior to folding and developed in response to along-strike stretching caused by the plunging shape of the foredeep. Joints developed in response to flexuring of the lithosphere at the peripheral bulge do not occur in the area, suggesting that this mechanism has limited relevance to the observed joint system. This is confirmed by the variability of joint orientations observed at the foredeep external edge, negating the occurrence of a major forebulge-perpendicular extension able to systematically orient the stress field at the foredeep edge.

Data availability

Digitized traces in shapefile format and bedding and joint data in csv format are in the supplementary materials

Author contributions

ST, PG, AC, TS, JMC, and JAM contributed equally to the elaboration of the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

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Captions

Figure 1

Scheme showing the architecture of a foreland fold-and-thrust belt and adjacent foredeep basin, with syn-orogenic fracture patterns in the different structural domains of the orogenic system. (A) The foredeep state of stress is governed by the permutation between the state of stress in the layer-parallel shortening and peripheral bulge domains. (B) The foredeep state of stress is controlled by the along-strike stretching of the foredeep.

Figure 2

Examples of pre-folding joints within the studied area. (A) N-S striking joint with plumose structures in the foredeep sediments (42°02'39.7"N; 2°13'54.9"E). (B) Tilted N-S and E-W striking joints in the southern limb of the Bellmunt anticline, with the red arrow indicating an E-W striking joint abutting on a N-S striking joint (42°05'39"N; 2°17'41.5"E). The density contours of poles to bedding and joints (in their present day orientation and after unfolding) refer to data collected in the Bellmunt anticline area. (C to F) Examples of joints seen on orthophotos. (C) Transverse joints. (D) N-S striking transverse joints with subordinate E-W striking cross-orthogonal joints. (E) NW-SE striking joints. (F) Rare example of multiple oblique sets occurring at the same exposure. Orthophotos are available from the Spanish Instituto Geográfico Nacional (https://pnoa.ign.es/).

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Figure 3

(A) Simplified geological map of the western Pyrenees and Catalan Coastal Ranges (based on the Geological Map of Catalunya scale 1:250’000; https://www.icgc.cat/en/Downloads), with N-S geological cross-section (modified from Parés et al., 1999). (B) Detailed geological map of the study area, with digitized joints (C). (D) Orthophoto (https://pnoa.ign.es/) of the study area, with digitized joints (E). (F) Frequency distribution of joint traces trend and length.

Figure 4

Examples of joint patterns and resultant Mv and R parameters calculated for the π and $\pi/2$ periods. For the five examples, we show the map view of the joints, the azimuthal frequency, and the sin-cos coordinates of the resultant values of Mv and R. Note that the distance from the center is proportional to R.

Figure 5

Results of circular statistics analysis for both Meshes 1 and 2. Length of traces of Mv_{π} is proportional to R_{π}. Color code refers to R_{π} and $R_{\pi/2}$, whereas the orientation of traces is the Mv. See text for details.

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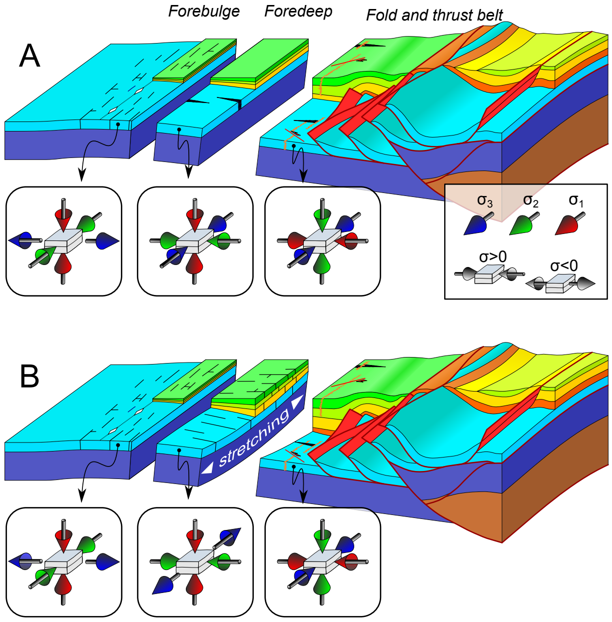

Figure 1 (Single column)
Scheme showing the architecture of a foreland fold-and-thrust belt and adjacent foredeep basin, with syn-orogenic fracture patterns in the different structural domains of the orogenic system. (A) The foredeep state of stress is governed by the permutation between the state of stress in the layer-parallel shortening and peripheral bulge domains. (B) The foredeep state of stress is controlled by the along-strike stretching of the foredeep.

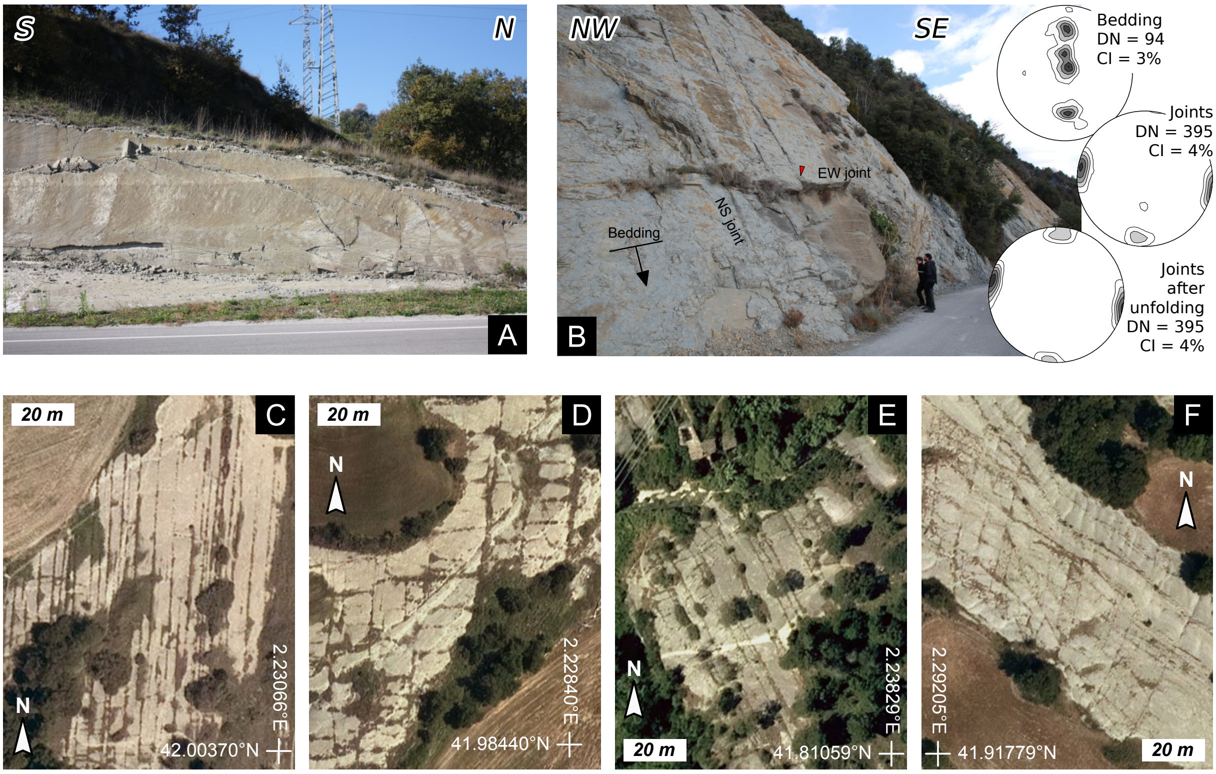

Figure 2 (Double column)

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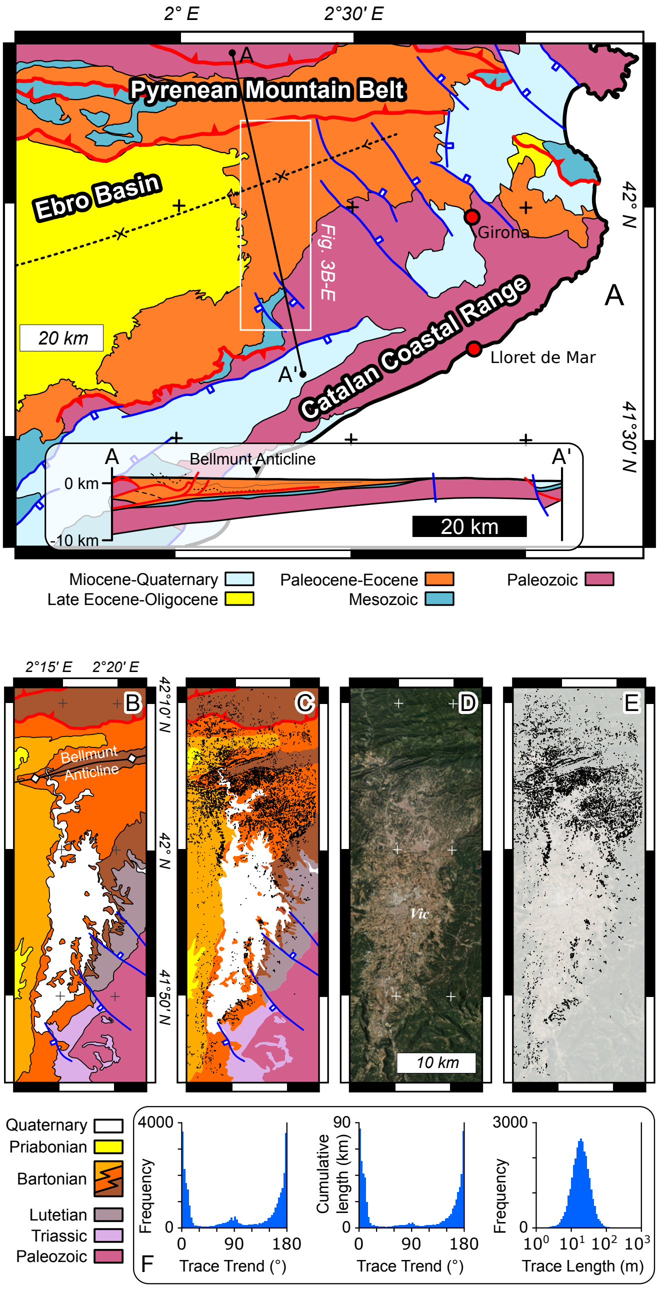

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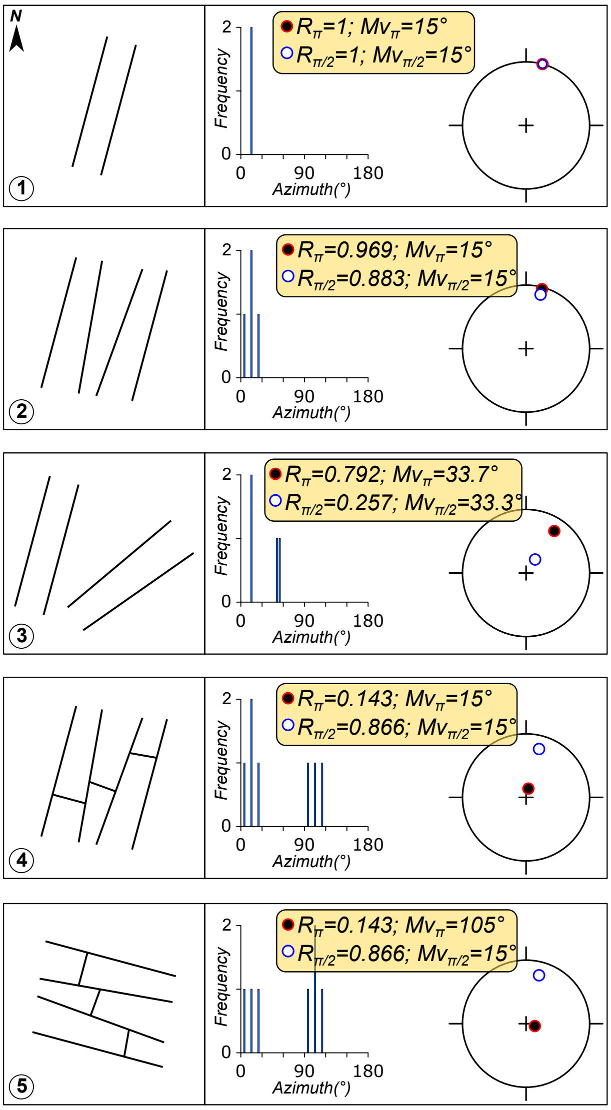

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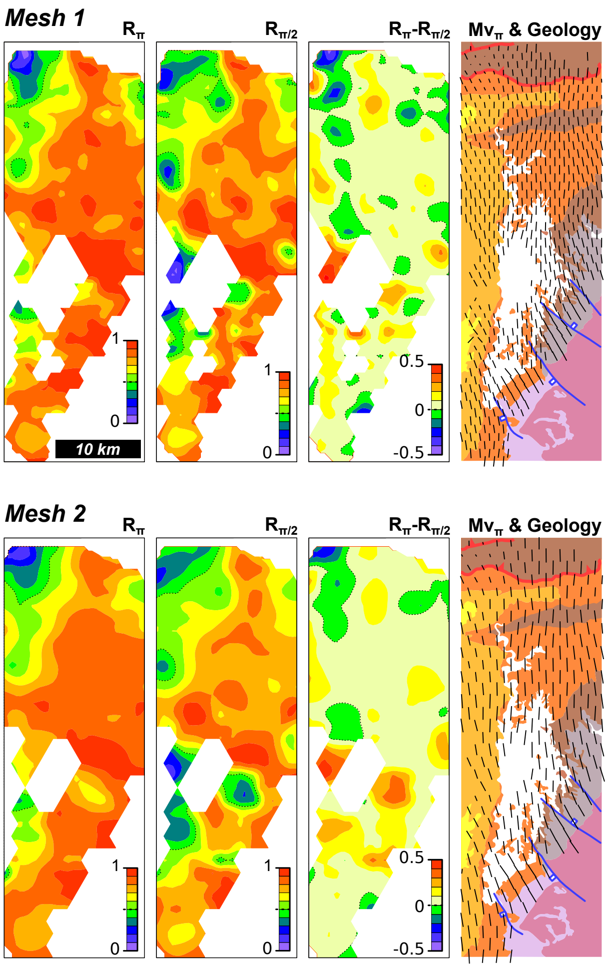
Examples of joint patterns and resultant Mv and R parameters calculated for the π and π/2 periods. For the five examples, we show the map view of the joints, the azimuthal frequency, and the sin-cos coordinates of the resultant values of Mv and R. Note that the distance from the center is proportional to R.



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Results of circular statistics analysis for both Meshes 1 and 2. Length of traces of $Mv\pi$ is proportional to $R\pi$. Color code refers to $R\pi$ and $R\pi/2$, whereas the orientation of traces is the Mv. See text for details. .