

A Probabilistic Approach for Identifying Independent Remote Compressions in an Intraplate Region: The Iberian Chain (Spain)

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Abstract The discrimination between distinct remote compressions and multiple local stress deviations within a single compressive stress field has been carried out in the central-eastern Iberian Chain, by using structural criteria, computing palaeostress directions, identifying and ‘filtering’ stress deviations, and analysing time relationships. A probabilistic analysis based on a systematic comparison of real and expected frequencies of coexistence of two compressions is applied by means of the χ^2 Test. This allows us to identify those tectonic compressions that behave as independent events from the probabilistic point of view. The results suggest that among five initially defined compression directions only three can be considered as representative of distinct (although partially superposed) externally applied intraplate stress fields: Iberian s.l. (NE-SW), Betic s.l. (NW-SE), and Pyrenean (N-S to NNE-SSW).

Keywords Palaeostress · Intraplate tectonics · Independent events · Chi-square test

Introduction

Stress fields are essentially non-homogeneous and frequently show strong variability in both space and time (Caputo 2005; Simón 1990). Distinct tectonic forces transmitted from plate margins can be either merged in an area (so defining a single stress field) or independently recorded one of each other (successive ‘tectonic phases’). On the other hand, faults and rheological discontinuities cause stress perturbations that strongly increase the variability of local stress axes. The distinction between both sources of heterogeneity is not an easy task.

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The Iberian Chain (Spain) is an intraplate, moderately deformed chain with an overall NW-SE trend (Fig. 1a), in which this problem has been discussed because of the great variety of stress directions recorded during the Tertiary compression (Fig 1b). Owing to its particular location within the Iberian Plate, this chain underwent tectonic compressions transmitted from both the Pyrenean and Betic active margins (compression trajectories roughly oriented NNE-SSW and SE-NW, respectively). Those compressions produced the positive inversion of a Mesozoic extensional basin, whose bounding faults were responsible, at the same time, for significant deviation of stress trajectories (Álvarez et al. 1979; Capote et al. 2002). Among the tectonic models proposed, some emphasize the succession of compressions related to different geodynamic forces (e.g. Simón 1982; De Vicente 1988; Muñoz-Martín 1997), whereas others invoke the existence of a single remote, nearly N-S trending compression together with a variety of stress deviations (Guimerà 1988; Casas et al. 1992).

According to some notions stated by Simón (1990), a systematic procedure was proposed by Liesa (2000) in order to assess the relative role that remote compressions and internal stress deviations take in the variability of stress axes recorded in the central-eastern Iberian Chain. This procedure included:

- (a) Exhaustive compilation of local compressive stress tensors all over the region, inferred by numerous authors who had used conventional methods of analysis on brittle structures. Only tensors with a nearly horizontal σ_1 axis have been considered (72% of them showed plunges lower than 10°). From the former tensors, those showing nearly vertical σ_3 axes represent 23%, while the strike-slip tensors (nearly vertical σ_2 axis) constitute 77%. As our aim is investigating intraplate transmission of compressive stress fields, extensional stress states (vertical σ_1 axis) were deliberately excluded.
- (b) Counting the overall frequencies of compression directions (trend of maximum stress axis σ_1).
- (c) Detecting stress deflections in order to distinguish and ‘filter’ local from remote stress directions. An accurate analysis of spatial distribution of σ_1 trends and their relationships with large-scale faults was achieved for this purpose.
- (d) Interpreting relative timing of local palaeostresses by analysing cross-cut relationships between brittle structures, so identifying coeval and non-coeval sets of compression directions.

After the careful application of this procedure, we were able to identify five groups of compression directions (Fig. 2), which can be easily correlated with those defined by previous authors (e.g. De Vicente 1988; Muñoz-Martín 1997): (1) Iberian compression: NE-SW; (2) Altomira compression: E-W; (3) Guadarrama compression: SSE-NNW; (4) Betic compression: two maxima, ESE-WSW and SE-NW; and (5) Pyrenean compression: NNE-SSW.

The timing of recorded stress states indicates that compressions ‘transverse’ to the overall trend of the Iberian Chain (Iberian, Altomira and Pyrenean) and those which are ‘longitudinal’ (Betic and Guadarrama) follow, respectively, two parallel sequences (Liesa 2000; Capote et al. 2002). A number of relationships found within the Betic set also show that SE compressive states tend to be younger than the ESE ones. On the other hand, contradictory time relationships have been found between Betic

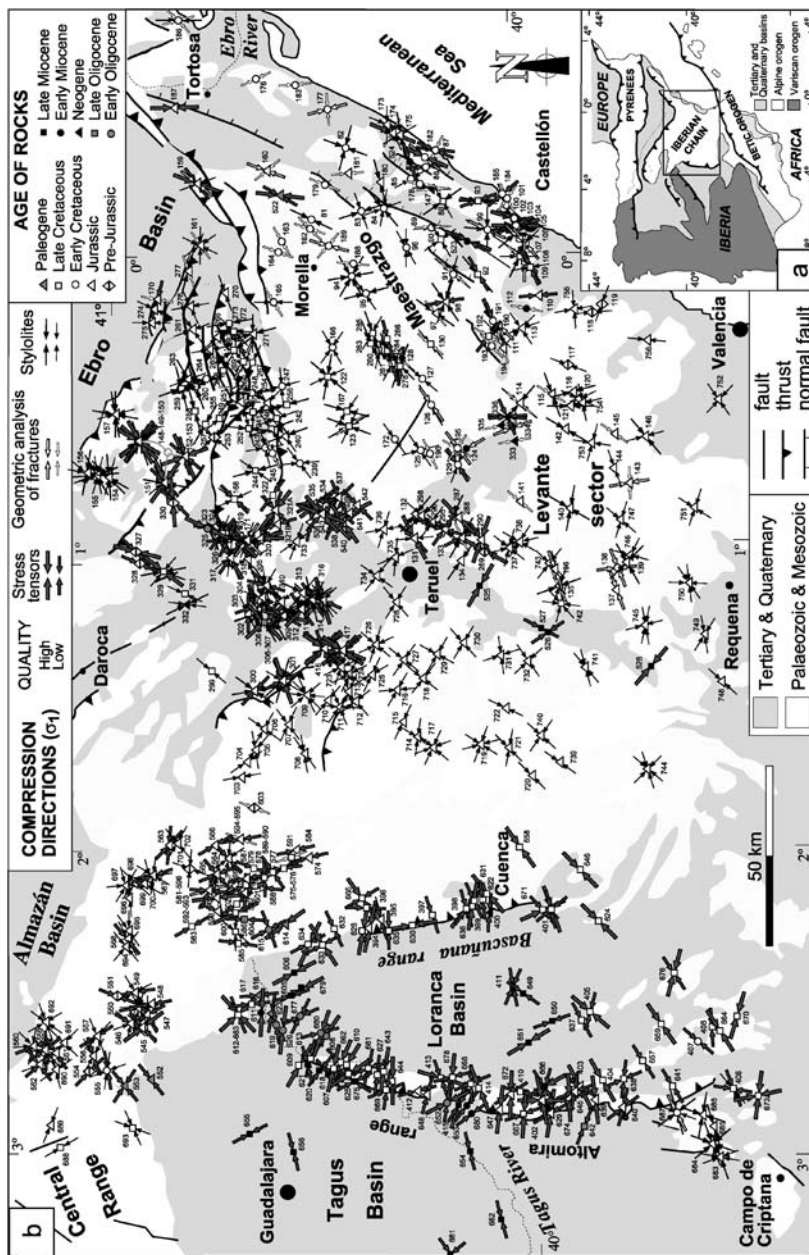
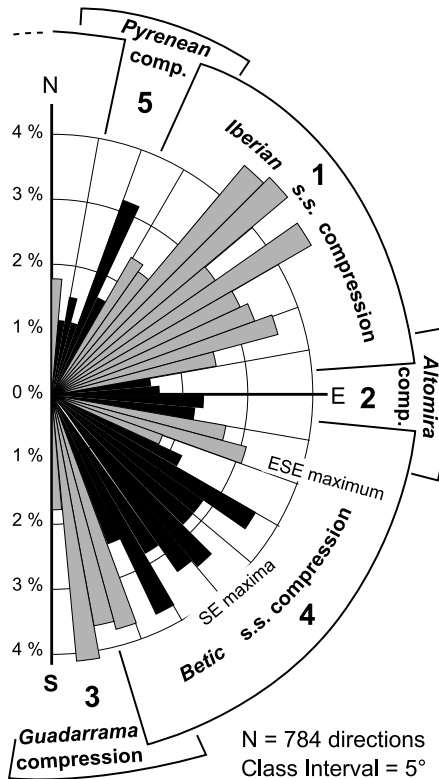


Fig. 1 **a** Location of the studied region within the Iberian Peninsula. **b** Compression directions (horizontal σ_1 axes) inferred from palaeostress analysis in the central-eastern Iberian Chain, as compiled by Liesa (2000). Different symbols are used according to the origin of results, quality of data samples, and age of deformed rocks

Fig. 2 Frequency distribution of compression directions (trends of maximum stress axes σ_1) in the central-eastern Iberian Chain. Alternating *black* and *grey* sectors within the rose diagram: azimuth intervals of the different groups of compression directions initially defined. Labelled arcs surrounding the rose: ‘genetic-meaning’ intervals defined after taking into account local stress deflections and timing of stress states



and Iberian compressive states, which could be compatible with two distinct scenarios: (a) cyclically alternating, overall coeval compressions; (b) an ESE-WSW→NE-SW→SE-NW compression sequence. Guadarrama compression should be considered as generally older than Pyrenean, although further regional structural and tectosedimentary information suggests that both could be partially coeval (Simón 2006).

Once we have defined (a) the azimuth intervals and the range of stress deflections within each compression direction, and (b) their timing patterns, a genetic meaning can be attributed to such compression directions. The ‘genetic’ azimuth intervals (represented by labelled arcs in Fig. 2, as opposed to the ‘statistical’ maxima represented in the rose diagram of the same figure), show partial overlapping in some cases according to the range of stress deviations. A careful observation of the neighbouring stress directions, and the subsequent reconstruction of hypothetical stress trajectories (Fig. 4), allowed us to set almost every local stress state within its proper genetic interval.

Nevertheless, we cannot guarantee that all these ‘genetic sets’ of compression directions represent compressive stress fields related to different externally applied tectonic forces. Briefly, within the kinematic framework of the Eurasian and African plates, the interior of the Iberian Plate was submitted during the Tertiary to the push of the Atlantic ridge together with convergent forces transmitted from both the northern (Pyrenean) and the southern (Betic) margins (Andeweg 2002; Andeweg et al. 1999). Could each of our five compressions result from an indepen-

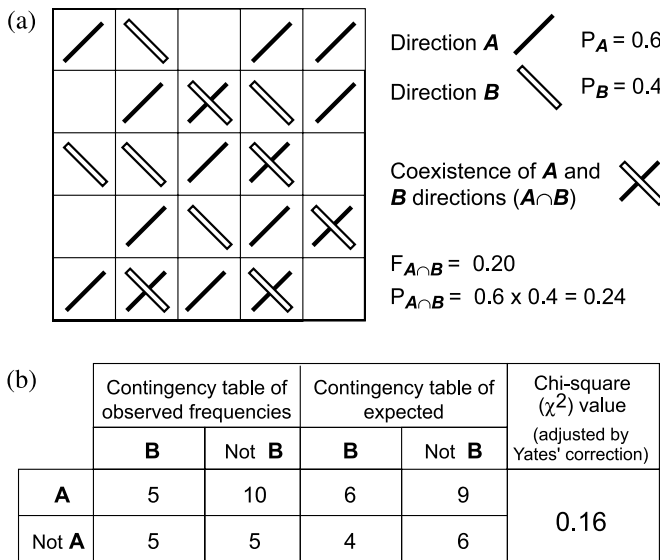


Fig. 3 **a** Schematic example illustrating the rationale of the probabilistic-statistical analysis of independence of two recorded compression directions (*A*, *B*), based on comparing their theoretic probability ($P_{A \cap B} = P_A P_B$) and real occurrence of coexistence ($F_{A \cap B}$). **b** Contingency tables for applying the χ^2 test

dent combination of such tectonic forces or, alternatively, could any of them represent a space/time variation of another?

Probabilistic Approach

Beyond classical approaches based on mere visual inspection of stress directions on maps, the solution for our problem can be approached by means of a simple probabilistic analysis, which tries to test the independence of such compressions. This procedure involves comparing the real frequency (*F*) of coexistence of two compressions (percentage of sites where they are recorded together) with the expected frequency (*P*) obtained according to the probability theory for independent events.

The probabilistic approach is based on the following assumptions:

- The probability of occurrence (*P*) of each compression direction can be empirically measured by its real frequency ($F_A = \text{number of sites recording direction A} / \text{total number of studied sites}$).
- If several σ_1 directions represent different primary, externally applied compressions, their occurrences at each site should be considered as independent events.
- If a given σ_1 direction is a local deflection of an externally applied compression, both events are not independent: the occurrence of the deviated direction ‘inhibits’ and diminishes the probability of occurrence of the external one. Both directions will tend to be found in different areas instead of being randomly mixed throughout the region.

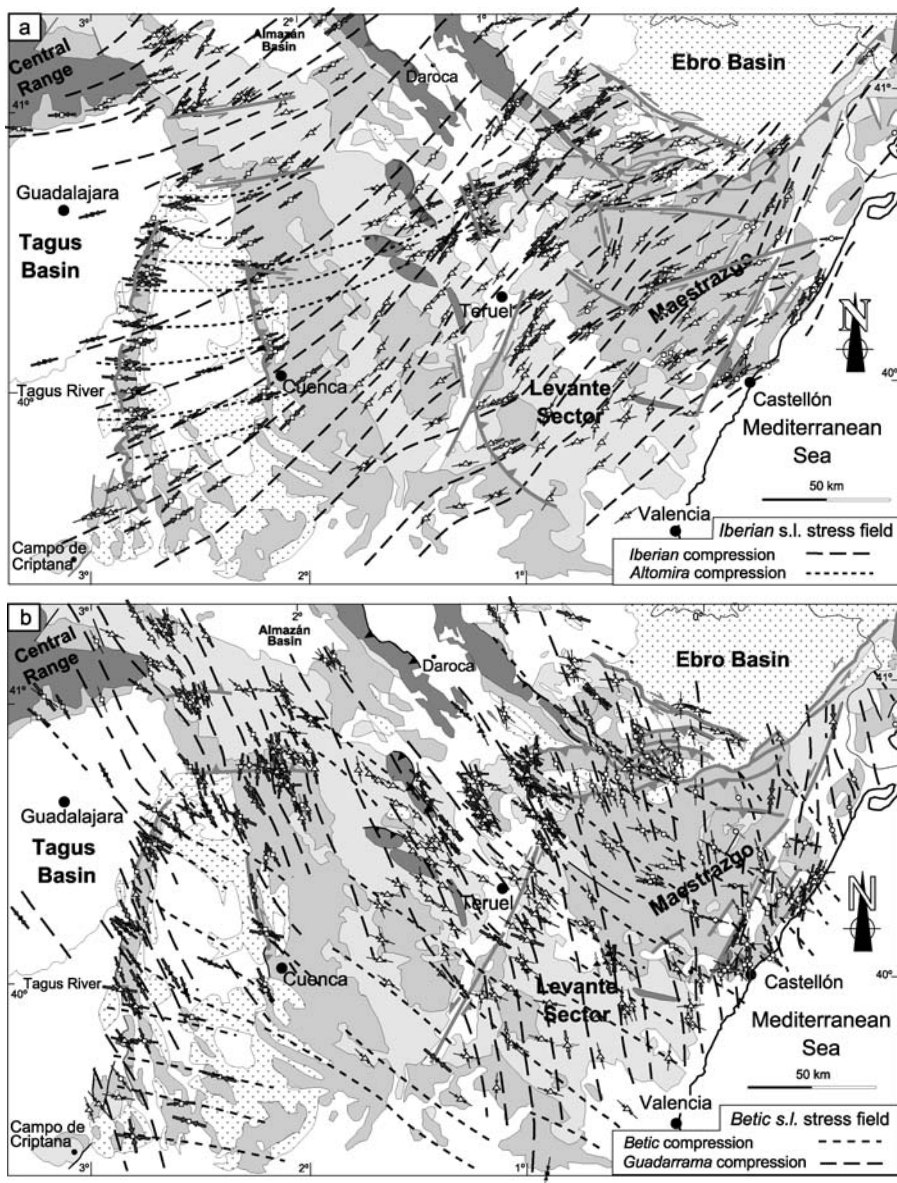


Fig. 4 The three independent, remote stress fields interpreted in the central-eastern Iberian Chain, showing local compressive stress states attributed to each of them (arrows) and inferred stress trajectories (dotted lines). **a** Iberian s.l. stress field. **b** Betic s.l. stress field. **c** Pyrenean stress field. Symbols as in Fig. 1

If the occurrences of two directions (A , B) are independent events, their probability of coexistence in a site will equal the product of their individual probabilities

$$P_{A \cap B} = P_A P_B \quad (1)$$

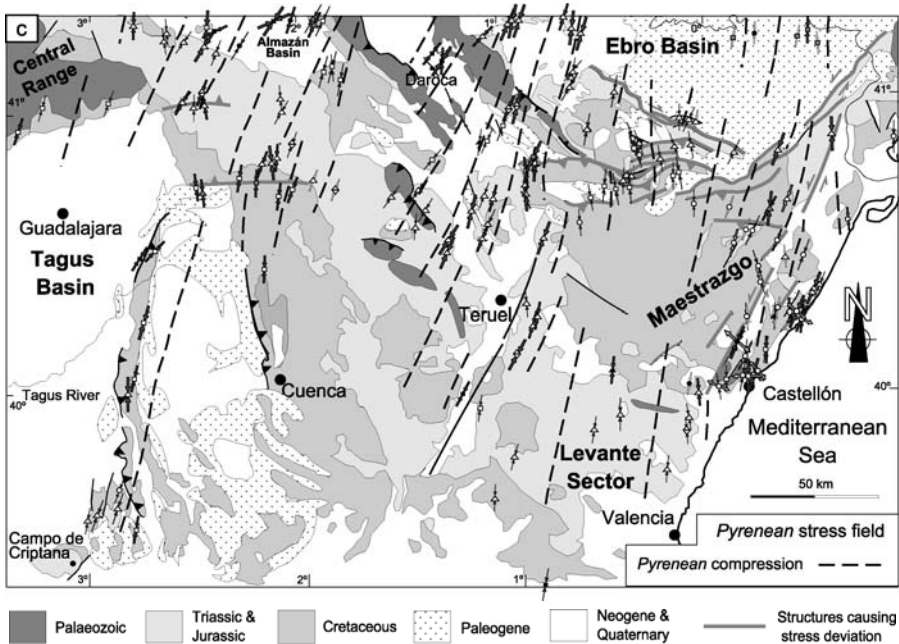


Fig. 4 (Continued)

As an example (Fig. 3a), if a compression direction A appears in 60% of sites and another independent direction B appears in 40% of them, their expected probability of coexistence is $P_{A \cap B} = 0.6 \times 0.4 = 0.24$. If we compare the real frequency of coexistence of two compression directions ($F_{A \cap B}$) with the expected frequency calculated by using (1), we will be able to discriminate if such directions represent either different externally-applied compressions randomly recorded across the region (independent events, $F_{A \cap B} \approx P_{A \cap B}$) or a case of stress deviation (non-independent events, $F_{A \cap B} < P_{A \cap B}$).

Results

Once each individual compression axis was assigned to one of the five “genetic sets”, the real occurrence of each stress direction in the studied region (F) was calculated by dividing the number of sites where it has been recorded by the total number of compiled sites (Table 1). The real frequencies of coexistence of two or more maxima ($F_{A \cap B}$) were counted in the same way, and their values were compared with the expected frequencies $P_{A \cap B}$ (Table 2).

Expected frequencies of coexistence of the different combinations of the five “genetic sets” generally agree with the real frequencies. This suggests that most of them represent independent stress fields. There are two exceptions: the combination of Altomira (2) with the other directions, and the combination of Guadarrama (3) with Betic (4).

Table 1 Real occurrence (F) of the five different compressions that were defined (see Fig. 3) from palaeostress states inferred in 479 sites of the central-eastern Iberian Chain

Compression	Real occurrence (F, %)
Iberian (1)	60.3
Altomira (2)	7.3
Guadarrama (3)	51.5
Betic (4)	39.4
Pyrenean (5)	5.0

The Altomira compression has not been found together with any other, except Guadarrama, despite the expected percentages of coexistence being relatively high (e.g. 4% in the case of coexistence of compressions 1 and 2). This could be a consequence of the heterogeneous distribution of the Altomira compression, only recorded in Altomira and Bascañana ranges where, on the contrary, the Iberian compression is poorly represented. This clearly implies a genetic relationship between Altomira and Iberian compressions, and agrees with the interpretation of their tectonic meaning by Liesa (2000). According to the author, regional stress trajectories indicate that the Altomira compression represents a large-scale deviation of the Iberian stress system (Fig. 4a), which could be achieved by a combination of two distinct mechanisms: (a) deflection by the Altomira-Bascañana thrust belt, with tendency of σ_1 trajectories to become orthogonal to thrust traces; and (b) clockwise rotation of regional compression at the westernmost sector of the Iberian Chain owing to the increasing influence of the Mid-Atlantic ridge push. Following this scenario, we have grouped Altomira (2) and Iberian (1) into the Iberian s.l. compression (designed as $1 \cup 2$), by recalculating the real frequency $F_{1 \cup 2} = F_1 + F_2$ (Table 3).

In the case of Guadarrama direction (3), the percentage of real coexistence with Betic (4) is slightly lower than the expected one (see Table 2). According to our criteria, both compressions should be interpreted as non-independent events, so they could represent natural fluctuations within a single stress field. Although the separate σ_1 maxima within the WNW-ESE to N-S interval could eventually represent different/successive stress events (according to the model of progressive clockwise rotation in time of the Betic compression proposed by Simón 1986, Guimerà 1988 and Liesa 2000), their narrow genetic relationship makes it difficult to discriminate between random space/time stress variations and clearly defined stress stages. In such a situation, we prefer following the procedure described above. Therefore, we group the Guadarrama (3) and Betic (4) compressions into Betic s.l. ($3 \cup 4$) and recalculate its real frequency (Table 3).

After grouping compressions $1 \cup 2$ and $3 \cup 4$, the real frequency of coexistence combining the three distinct so-defined sets is different from 0 and approaches the expected frequency $P_{A \cap B}$ (Table 4). The Iberian s.l. ($1 \cup 2$), Betic s.l. ($3 \cup 4$) and Pyrenean (5) compressions behave as true independent events and are compatible with three different primary, far-field tectonic stress systems.

Table 2 Real (F) and expected (P) frequencies of coexistence of the possible combinations between the five compressions (Fig. 3). Numbers as in Table 1

Compression	Coexistence (%)	
	Real frequency “F”	Expected frequency “P”
1∩2	0	4.4
1∩3	25.6	31.0
1∩4	25.2	23.7
1∩5	3.1	3.0
2∩3	2.7	3.7
2∩4	0	2.8
2∩5	0	0.3
3∩4	14.4	20.2
3∩5	1.4	2.5
4∩5	2.5	1.9
1∩2∩3	0	2.2
1∩2∩4	0	1.7
1∩2∩5	0	0.2
1∩3∩4	8.1	12.2
1∩3∩5	1.2	1.5
1∩4∩5	1.8	1.1
2∩3∩4	0	1.4
2∩3∩5	0	0.2
2∩4∩5	0	0.1
3∩4∩5	0.6	1.0
1∩2∩3∩4	0	0.8
1∩2∩3∩5	0	0.11
1∩2∩4∩5	0	0.08
1∩3∩4∩5	0.4	0.6
2∩3∩4∩5	0	0.07
1∩2∩3∩4∩5	0	0.04

Table 3 Real frequency of occurrence (F) of the different compression directions once Altomira and Iberian were grouped ($1 \cup 2$), and Guadarrama and Betic were grouped ($3 \cup 4$)

Compression	Real occurrence (F, %)
1 ∪ 2	67.6
3 ∪ 4	76.5
5	5.0

Applying the χ^2 Test

The significance of the difference between the expected and observed frequency values has been evaluated by using the Chi-Square (χ^2) Test. We consider that the null

Table 4 Real (F) and expected (P) frequencies of coexistence of the possible combinations between compressions $1 \cup 2$, $3 \cup 4$ and Pyrenean (5)

Compression	Coexistence (%)	
	Real frequ. “F”	Expect. frequ. “P”
$(1 \cup 2) \cap (3 \cup 4)$	45.5	51.7
$(1 \cup 2) \cap 5$	3.1	3.3
$(3 \cup 4) \cap 5$	3.3	3.8
$(1 \cup 2) \cap (3 \cup 4) \cap 5$	2.7	2.5

Table 5 Chi-Square (χ^2) index values for testing the independence of the five compressions

Chi-square (χ^2) index				
For pairs of individual genetic intervals				
	Altomira (2)	Guadarrama (3)	Betic (4)	Pyrenean (5)
Iberian (1)	53.99	22.70	1.54	0
Altomira (2)		2.49	23.41	1.01
Guadarrama (3)			27.43	4.21
Betic (4)				0.73
Grouping Iberian and Altomira ($1 \cup 2$)				
		Guadarrama (3)	Betic (4)	Pyrenean (5)
$1 \cup 2$	35.52	1.58	0.09	
Guadarrama (3)			27.43	4.21
Betic (4)				0.73
Grouping Iberian and Altomira ($1 \cup 2$) and Betic and Guadarrama ($3 \cup 4$)				
			Betic ($3 \cup 4$)	Pyrenean (5)
$1 \cup 2$			44.53	0.09
$3 \cup 4$				0.78

hypothesis H_0 states that the local record of each σ_1 direction is random. Thus, a σ_1 direction does not condition the occurrence of another. Contingency tables of every combination of occurrence/non occurrence of the analysed compression directions were elaborated in order to calculate χ^2 values. As the studied problem only has one degree of freedom and the computed absolute frequencies are low, Yates' correction was applied (Davis 1986; Marsal 1987)

$$\chi^2 = (|O_1 - E_1| - 0.5)^2/E_1 + (|O_2 - E_2| - 0.5)^2/E_2 + \dots + (|O_n - E_n| - 0.5)^2/E_n$$

As an example, the contingency tables of the observed and expected occurrences of compressions A and B are shown in Fig. 3b, and then the χ^2 index is calculated. The obtained value $\chi^2 = 0.16$ is much lower than the reference value $\chi^2_{95\%} = 3.84$, so H_0 cannot be rejected, and we should admit the randomness of occurrence of compressions A and B.

Table 5 shows the χ^2 values obtained for every pair of compression directions in the same way. These values corroborate: (a) the independence of the Pyrenean compression with respect to the Iberian, Altomira and Betic compressions ($\chi^2 < 3.8$), the result for the Pyrenean/Guadarrama pair ($\chi^2 = 4.21$) not being conclusive; and (b) the non-independence of Iberian/Altomira and Betic/Guadarrama. On the contrary, χ^2 values for pairs 1/3 (Iberian/Guadarrama) and 2/4 (Altomira/Betic) also indicate non-independence, different from the result of the probabilistic approach. In our opinion, such eventual non-independence should not be interpreted as a ‘genetic relation’ similar to the Iberian/Altomira and Betic/Guadarrama pairs. The angle between Guadarrama and Iberian compressions (Fig. 2) clearly exceeds the highest deviation ranges estimated from regional reconstruction of stress trajectories and the finite-element numerical simulation (± 20 – 25° ; Liesa 2000). This makes the hypothesis that one of them could be a large-scale deviation of the other quite improbable (in fact, almost dynamically incompatible). An inhomogeneous spatial distribution of the Guadarrama compression, better represented in the southeastern part of the studied region (Figs. 1b, 4b), could be a more reliable alternative explanation. In the case of Altomira/Betic pair, difficulties in the assignation of ESE-WNW compression directions to either one or another genetic interval could be responsible for the result obtained. Within the Altomira-Basculana sector, two closely oriented σ_1 axes appearing in a given site have been frequently attributed to a single genetic interval, by excluding the possibility of coexistence of both compressions.

Conclusions

Five groups of compression directions were initially distinguished in the frequency distribution of azimuths of local σ_1 (maximum stress) axes recorded in the central-eastern Iberian Chain: (1) Iberian compression, NE-SW; (2) Altomira compression, E-W; (3) Guadarrama compression, SSE-NNW; (4) Betic compression, ESE-WSW to SE-NW; (5) Pyrenean compression, NNE-SSW. After characterizing their range of spatial variability and time relationships, an azimuth interval with ‘genetic’ meaning was defined for each compression direction (Fig. 2).

The probabilistic analysis of the overall compression record, based on the comparison of real and expected percentages of coexistence of distinct compressions, allows us to interpret that only three such compressions behave as independent stress systems. We designate them as Iberian s.l., Betic s.l. and Pyrenean compressions, respectively. The three independent stress systems can be identified with far-field tectonic stress fields originated by distinct combinations of forces transmitted from the Iberian plate margins during Tertiary times. Some of them could be partially superposed during some time periods (Liesa 2000). Moreover, they undergo local and regional stress deflections that produced a moderate variability of stress trajectories.

The Iberian s.l. stress field includes the Iberian (NE-SW) and Altomira (E-W) compressions. The latter has been interpreted as a result of stress deviation, mainly produced in the Altomira and Basculana ranges (westernmost Iberian Chain) (Fig. 4a). The Betic s.l. stress field includes the Betic (WNW-ESE to NW-SE) and Guadarrama (NNW-SSE) compressions, where the transition between them is possible in both space and time (Fig. 4b). And finally, the Pyrenean stress field includes

the Pyrenean compression (Fig. 4c), and probably represents the most recent tectonic stress field recorded all over the region.

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