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# Structural evolution of the Benicàssim area (Maestrat basin, NE Spain): insights from fracture and vein analysis

### *Evolución estructural de la zona de Benicàssim (Cuenca del Maestrat, NE España): resultados a partir del análisis de fracturas y venas*

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## *ABSTRACT*

*The Benicàssim area, in the Maestrat Basin, is affected by structures of different scale that are the result of several tectonic events. This contribution presents an outcrop-scale analysis of orientations and relative timing of fractures, striations and veins. The results indicate that there are fractures with the following strikes: N-S, NNE-SSW, E-W y NW-SE. They have striations that record different movement directions: (#1) dip-slip in fault planes oriented N-S and E-W that indicate normal fault movement; (#2) strike-slip in NNE-SSW to N-S-oriented fractures and conjugate sets of en-echelon calcite veins; (#3) reverse oblique-slip reverso in faults oriented NNE-SSW y N-S; and finally (#4) tilting of layers towards the NE to NW, with layer-parallel slipping.*

***Key-words:*** *Fault, fracture, vein, paleostress, Maestrat or Maestrazgo Basin.*

## *RESUMEN*

*La zona de Benicàssim, en la Cuenca del Maestrat, está afectada por estructuras de diferentes escalas que registran diversos episodios de deformación. Este trabajo presenta un análisis de orientaciones y relaciones temporales de fracturas, estrías y venas a escala de afloramiento. Los resultados indican que existen fracturas con orientaciones aproximadas N-S, NNE-SSW, E-W y NW-SE con estrías que registran varios movimientos: (#1) dip-slip en fallas N-S y E-W que indica deslizamiento como fallas normales; (#2) strike-slip en fallas NNE-SSW y N-S y venas conjugadas de calcita en-echelon; (#3) oblique-slip reverso en fallas NNE-SSW y N-S; y finalmente (#4) basculamiento de las capas hacia el NE a NW, con deslizamiento paralelo a los estratos. Estos movimientos muestran la compleja historia tectónica de la zona y están relacionados con los siguientes episodios: rifting del Cretácico Inferior, inversión Alpina y extensión Neógena.*

***Palabras clave:*** *Falla, fractura, vena, paleoesfuerzos, Cuenca del Maestrat o Maestrazgo.*

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## Introduction and geological setting

The Benicàssim area (Fig. 1) is part of the Maestrat Basin and constitutes the eastern margin of the Desert de Les Palmes ranges. This basin was formed during the Late Jurassic - Early Cretaceous rifting cycle (Roca *et al*., 1994; Salas *et al*., 2001). It was subsequently uplifted during the Alpine Orogeny into the Iberian Chain. In the Benicàssim area, thick sequences (~ 1,500 - 2,000 m) of shallow-marine carbonates, mainly Aptian in age, overlie ~ 600 m of Permo-Triassic rocks (mainly siliciclastic) and basement shales and slates of Carboniferous age.

Some of the syn-rift Aptian carbonate beds appear partially dolomitised over several kilometres, with a wavy stratiform geometry. This area is an outcrop analogue of partially dolomitised oil and gas reservoirs. The dolomitisation process has been extensively studied due to its economic importance (e.g. Martín-Martín *et al*., 2010). Mississippi Valley type (MVT) ore deposits of Early Paleocene age (Grandia, 2001) appear hosted by dolomites near fault zones.

Several seismic-scale faults crop out in the area and compartmentalise the rocks into several blocks (Fig. 1): the Benicàssim fault, with NNE-SSW strike, and the E-W striking Campello and Juvellús faults. They are subparallel to structures of the Catalan Coastal Ranges and the linking zone. Roca *et al*. (1994) suggested that a large accommodation space was created on the hanging wall of the Benicàssim fault during the Early Cretaceous, allowing the sedimentation of a thick pile of carbonates. Aptian sediments in this area are considerably thicker than in other areas of the Maestrat basin. These large faults have offsets of over one km, affect the basement, and were presumably reactivated during the Alpine compression and Neogene extension.

Besides the seismic-scale faults, a network of sub-seismic scale fractures, parallel to the large structures, affects the Mesozoic carbonates in the area. The different generations and movements of these structures are still not clear. However, it is essential to unravel the structural evolution of the area, due to its economic importance and its stratigraphic particularities (i.e. anomalous thickness of Aptian sediments). For this purpose we summarise in this contribution the results of a tectonic survey on sub-seismic-scale structures.

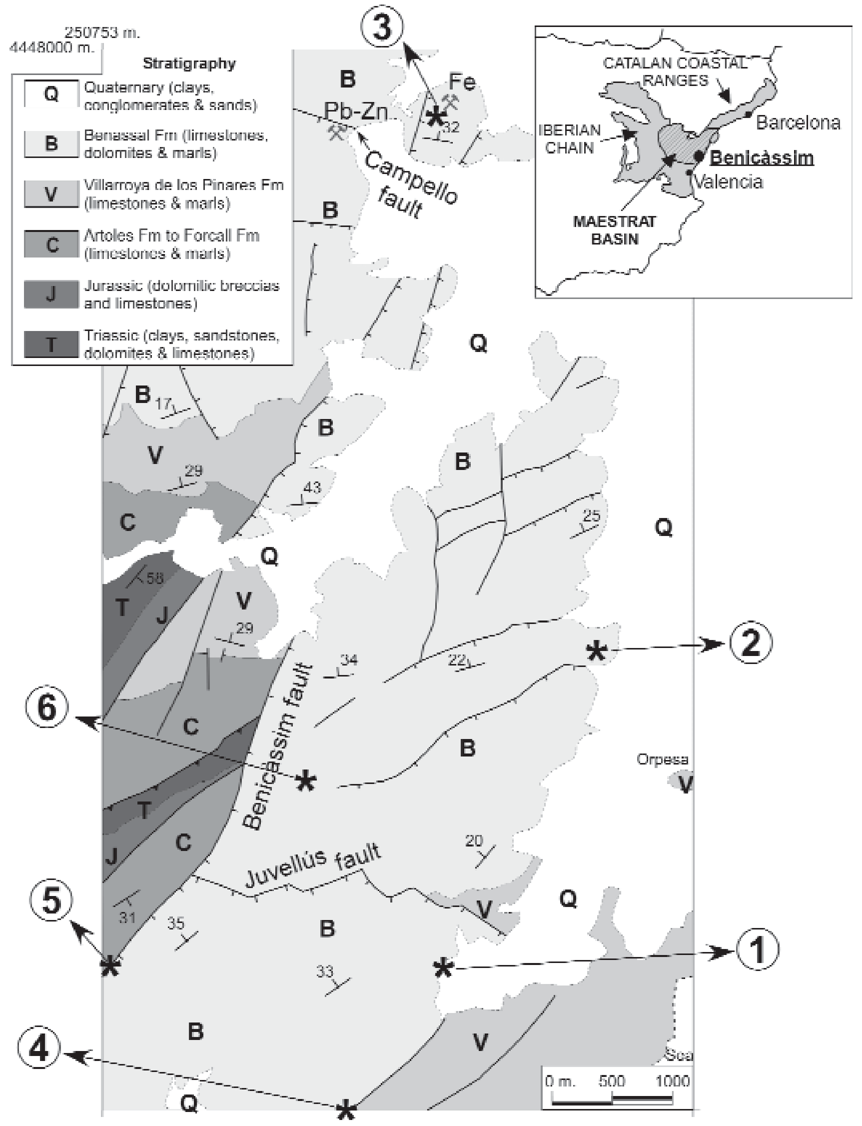

**Fig. 1.- Simplified map of the Benicàssim area with the localities analysed in this study.**

*Fig. 1. Mapa simplificado de la zona de Benicàssim con los afloramientos analizados.*

## Methods

We have collected over 300 orientations of fractures, faults and veins, shear sense indicators as well as striations on exposed planes in order to identify the different generations of structures in detail. Overprinting relationships between the various structures are used to constrain the structural evolution of the Benicàssim area. This survey has been performed in several outcrops of the study area, mainly in quarries (Fig. 1, Table I). In the next section we report the different structures we have found at each outcrop organised by relative age.

## Results

The first event (#1) that can be clearly recognised is normal (dip-slip) faulting (Figs. 2,3). Three main fault orientations have subvertical striations. They strike NNE-SSW to NE-SW, E-W and NW-SE. The first two orientations are subparallel to the main faults in the area (Campello, Juvellús and Benicàssim faults; Fig. 1) and dip towards the South and East, respectively. An additional fault set with dip-slip movement is recognised in one of the outcrops. This third set also strikes NNE-SSW (Fig. 3, locality 3) but dips towards the WNW, being conjugate with the one parallel to the Benicàssim fault.

The second main event (#2) is strike-slip deformation and can be recognised from many subhorizontal striations on fault planes as well as conjugate sets of en-echelon veins. Strike-slip striations are present on many N-S to NNE-SSW striking faults and always appear postdating dip-slip striations. Conjugate sets of en-echelon veins have been identified near the Benicàssim fault (Figs. 1,2,3). They have a vertical intersection, with horizontal $\sigma_1$ and $\sigma_3$ principal stresses. The first generation of en-echelon veins (#2.1) corresponds to WSW-ENE-oriented compression, while the second one (#2.2) was formed as a consequence of SW-NE-directed compression (Figs. 2,3).

| Locality | *n* Data |
|---|---|
| **1**. Racó de Rita quarry | |
| – fractures | 14 |
| – striations | 6 |
| **2**. Racó de Peret quarry | |
| – fractures | 26 |
| – striations | 20 |
| **3**. Mortorum Fe mine | |
| – fractures | 17 |
| - striations | 18 |
| **4**. Torre del Bellver quarry | |
| – fractures | 29 |
| – striations | 14 |
| **5**. Benicàssim fault - Artoles Fm | |
| – calcite veins | 27 |
| **6**. Benicàssim fault - Benassal Fm | |
| – calcite veins | 8 |

**Table I.- List of localities and number of data plotted for each area.**

*Tabla I.- Listado de afloramientos y cantidad de datos obtenidos en cada área.*

Some of the NNE-SSW to N-S striking faults have striations that recorded a reverse oblique-slip movement. These structures correspond to event #3, are postdating dip-slip striations and indicate that E blocks were moving upwards. It is important to notice that crosscutting relationships between events #2 and #3 are not clear, so we have ordered these two events according to their coincidence with orientations of the main regional structures (e.g. Capote *et al*., 2002; Liesa and Simón, 2009).

Finally, layer-parallel slipping (event #4) offsets all the pre-existing structures in one of the outcrops. This suggests that the present 30º-40º tilting of layers towards the NW to NE is the most recent event.

## Discussion and conclusions

In this contribution we present a preliminary field survey of outcrop-scale structures with the objective of constraining the structural evolution of the Benicàssim area. Four main events have been recognised: (#1) normal (dip-slip) deformation, (#2) strike-slip deformation, (#3) reverse oblique-slip deformation and (#4) layer tilting.

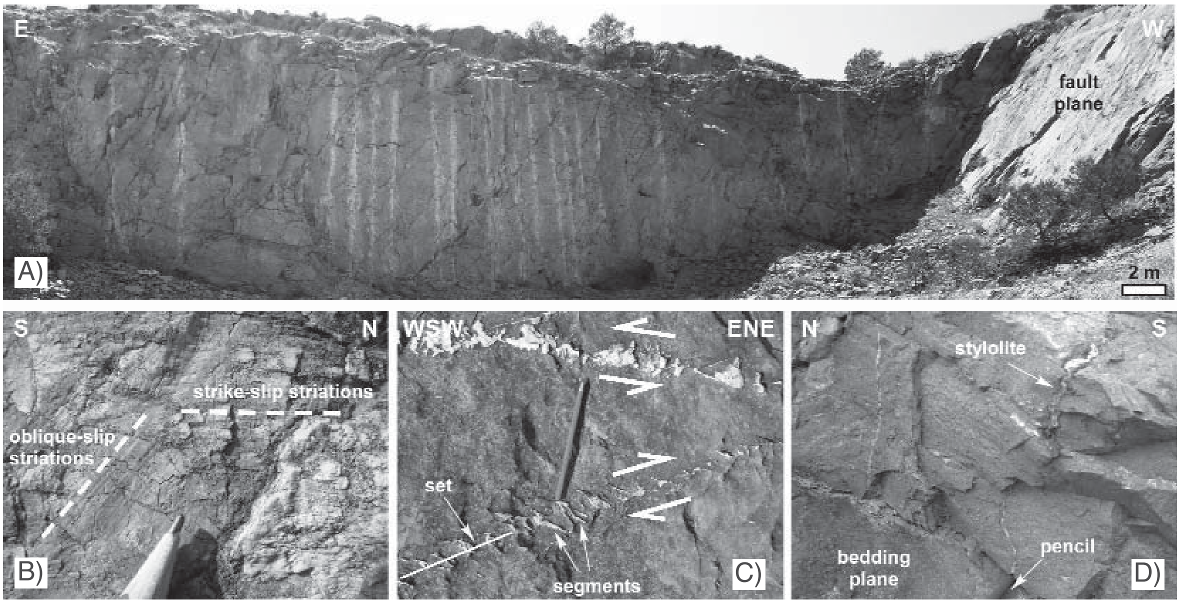

**Fig. 2.- Details of structures: A) View quarry of locality 2; B) Overprint of striations on a NNE-SSW striking fault (locality 2); C) Conjugate sets of dextral and sinistral en-echelon calcite veins (locality 5); D) Tectonic stylolite filled with calcite and overprinted by layer-parallel slipping (locality 4).**

*Fig. 2. Detalles de estructuras: A) Cantera del afloramiento 2; B) Superposición de estrías en una falla NNE-SSW (afloramiento 2); C) Familias de venas de calcita conjugadas en-echelon (afloramiento 5); D) Estilolito tectónico relleno de calcita y superpuesto por un deslizamiento entre capas (afloramiento 2).*

The differences in thickness of the Benassal Fm between Benicàssim and other areas of the Maestrat basin reported in previous studies (e.g. Bover-Arnal *et al.*, 2009) suggests that the large scale faults in the area acted as normal faults during the Early Cretaceous rifting period, causing differences in accommodation space between different blocks. Therefore, event #1 is interpreted to represent the Early Cretaceous rifting cycle described by Salas *et al.* (2001). Measured orientations of these structures are in accordance with those found in other areas of the basin related to this rifting cycle (Capote *et al.*, 2002; Antolín-Tomás *et al.*, 2007). Estimates of burial depths from sedimentary stylolites also suggest differences between fault blocks (Kulzer, 2011). This supports the idea of a synsedimentary, predominant dip-slip movement on these faults. Outcrop-scale faults could have been formed within the Early Cretaceous carbonates during successive slip episodes of the seismic-scale structures.

Subhorizontal striations related to strike-slip deformation (#event 2), present on many N-S to NNE-SSW oriented fault planes, are postdating dip-slip striations and indicate NE-SW-oriented compression. Two events of strike-slip deformation can also be recognised from conjugate en-echelon veins. We have not found cross-cutting relationships between these sets of veins and other structures, but their horizontal $\sigma_1$ and $\sigma_3$ suggest that they could have been formed at the same time as the strike-slip fault event. They indicate an anticlockwise rotation of $\sigma_1$ from WSW-ENE (event #2a) to NE-SW (event #2b). Tectonic stylolites in the area have an average orientation of 060/40 (dip dir./dip; Kulzer, 2011), which is compatible with event #2b. These events (#2a, #2b) have been described in many other areas of the Iberian Chain (Liesa and Simón, 2009) and correspond to the Alpine Orogeny.

Reverse oblique-slip striations (#event 3) are the result of the inversion of some of the N-S to NNE-SSW striking faults, as indicated by their cross-cutting relationships. These structures are compatible with a N-S to NNW-SSE-oriented Alpine compression, which has also been reported in the Iberian Chain by Liesa and Simón (2009).

The final tilting of layers towards the NW to NE seems to be the most recent event (#4). This is suggested by the late layer-parallel slip and also by the coincidence of the structures of previous events between the different outcrops when orientation data are rotated with bedding being on the horizontal plane. This movement is probably associated to the Neogene extension period, as suggested by previous authors (e.g. Antolín-Tomás, 2007 and references therein).

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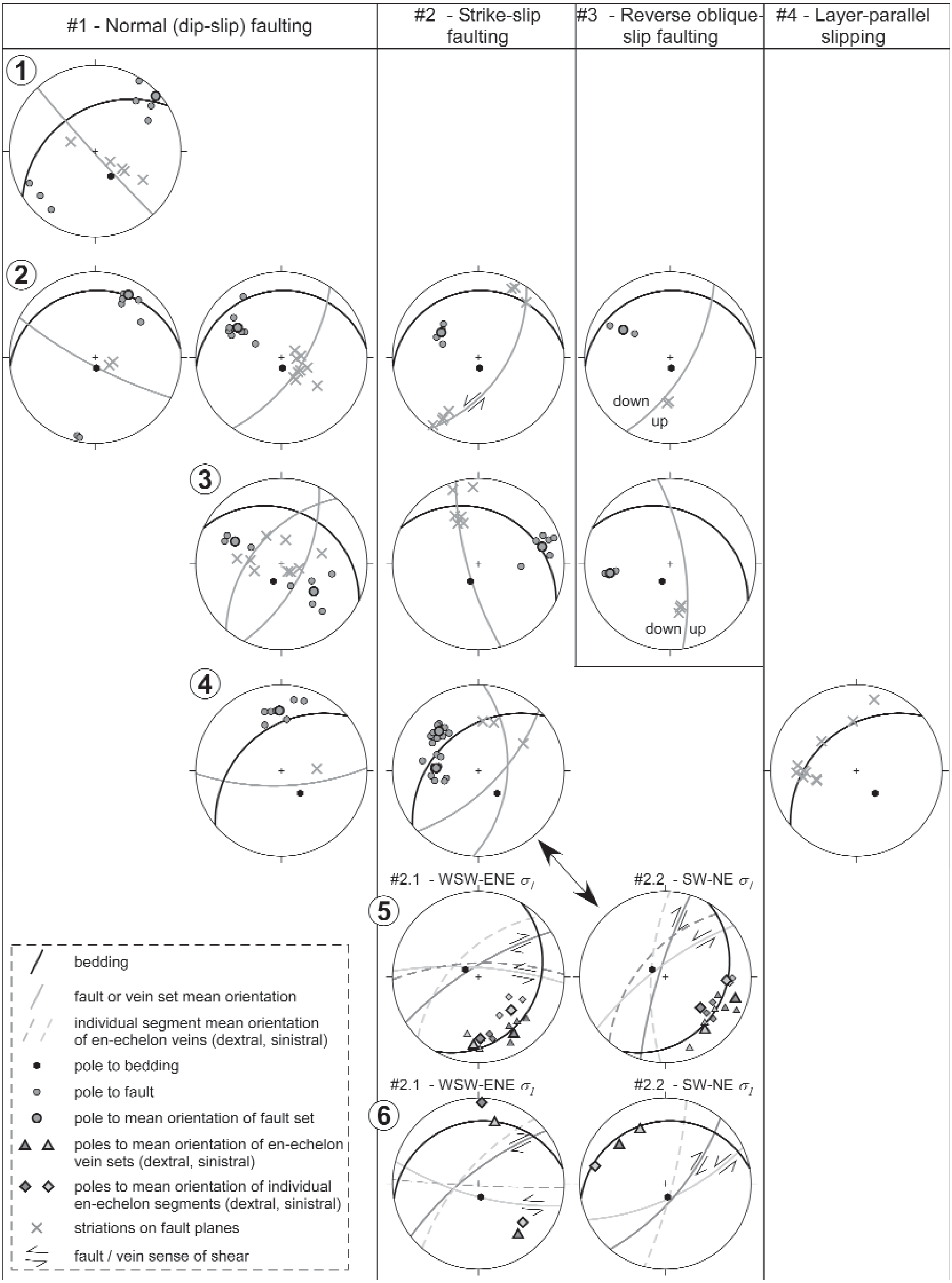

**Fig. 3.- Summary of the structures that have been found and analysed. Each row (1-6) correspond to one outcrop (see Fig. 1 and Table I).**

***Fig. 3. Resumen de las principales estructuras que se han encontrado y analizado. Cada fila (1-6) corresponde a un afloramiento (ver Fig. 1 y Tabla I)***