Folding and fracturing relationships from Jurassic limestones of South Rifian Ridges, Northern Morocco

Fracturación asociada a pliegues en las calizas jurásicas de las cadenas del Sur del Rif (Marruecos)

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ABSTRACT

The study of fractures affecting the Jurassic Ridges of Fert El Bir, Kefs and Outita from South Rifian Ridges, Northern Morocco, allowed us to propose a folding-fracturing model that summarizes the distribution of fractures within fault-propagation folds and the chronology of the different families of fractures occurring during the history of Miocene and Quaternary shortening phases, oriented NE-SW. At the beginning of compressional phase, sedimentary series corresponding mainly to limestones are deformed by layer parallel shortening (LPS) accompanied by pure shear causing thickening with the occurrence of oblique and transverse fractures. Following the establishment of the ramp fold, existing fractures are locally affected by simple shear within the two flanks of the fold and axial fractures are developed as a response of the accommodation of the surface folding.

Key-words: *Folding, fracturing, fault-propagation folds, Jurassic, South Rifian Ridges, Morocco.*

RESUMEN

A partir del estudio de la fracturación en los materiales jurásicos de las estribaciones del sur de las cadenas rifeñas (norte de Marruecos), se propone un modelo de plegamiento y fracturación que explica la distribución de fracturas en pliegues de propagación de fallas, así como la cronología de las distintas familias de fracturas formadas durante la historia deformacional del Mioceno y Cuaternario (compresión NE-SW). Al comienzo de la etapa compresiva, las secuencias sedimentarias sufrieron una deformación por acortamiento paralelo a las capas (layer-parallel shortening, LPS), acompañada de cizalla pura que trajo como resultado el engrosamiento de las capas y la aparición de fracturas oblicuas y transversas. Después del emplazamiento del pliegue asociado a la falla, las fracturas sufrieron desplazamientos en los dos flancos del pliegue, y se formaron nuevas fracturas como resultado de la acomodación a la superficie de plegamiento.

Palabras clave: *Pegamiento, fracturación, pliegue de propagación de falla, Jurásico, cadenas sur-rifeñas, Marruecos.*

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Introduction

In spite of the advances made in the knowledge of the South Rifian Ridges (SRR) in the last decades (Faugères, 1978; Haddaoui, 2000; Bargach *et al*., 2004; Chalouan *et al*., 2006; Sani *et al*., 2007; Habibou *et al*., 2012; Roldán *et al*., 2014), important issues including folding and fracturing relationships remain unsolved. The SRR are located at the frontal part of the Rif Cordillera. They comprise elongated hills, formed mainly by Jurassic rocks. The SRR are grouped into two great ensembles separated by the Volubilis depression (Fig. 1). The SRR are formed by a sedimentary sequence starting with Triassic evaporitic rocks, a thick Jurassic sequence, mainly carbonatic, and locally, a marly Cretaceous series in the Eastern Ridges. Unconformable Lower and Middle Miocene marls as well as sandstones of Middle-Upper Miocene overlay the Mesozoic series. The SRR correspond generally to anticline hinges of SW and S vergence located in the mountain front and associated with thrusts of the Prerif nappe sheets. They are complex folds, with a kilometric length and periclinal ends. Recent structural studies (Haddaoui, 2000; Sani *et al*., 2007; Habibou *et al*., 2012) interpreted these structures as ramp propagation folds born on the main thrusts, which in this region probably started to develop since the Early Miocene. The most active deformation phase affecting Pliocene rocks consisted of N-S to NE-SW oriented compression (Chalouan *et al*., 2006; Sani *et al*., 2007). Our work in this region is to develop a kinematic model from the analysis of fractures affecting Jurassic limestones in three anticlines: Fert El Bir in the Eastern arc and Kefs and Outita in the Western arc.

Methodology: analyses of fractures

The fractures developed on the Liassic limestones of Jebel Fert El Bir, Kefs and

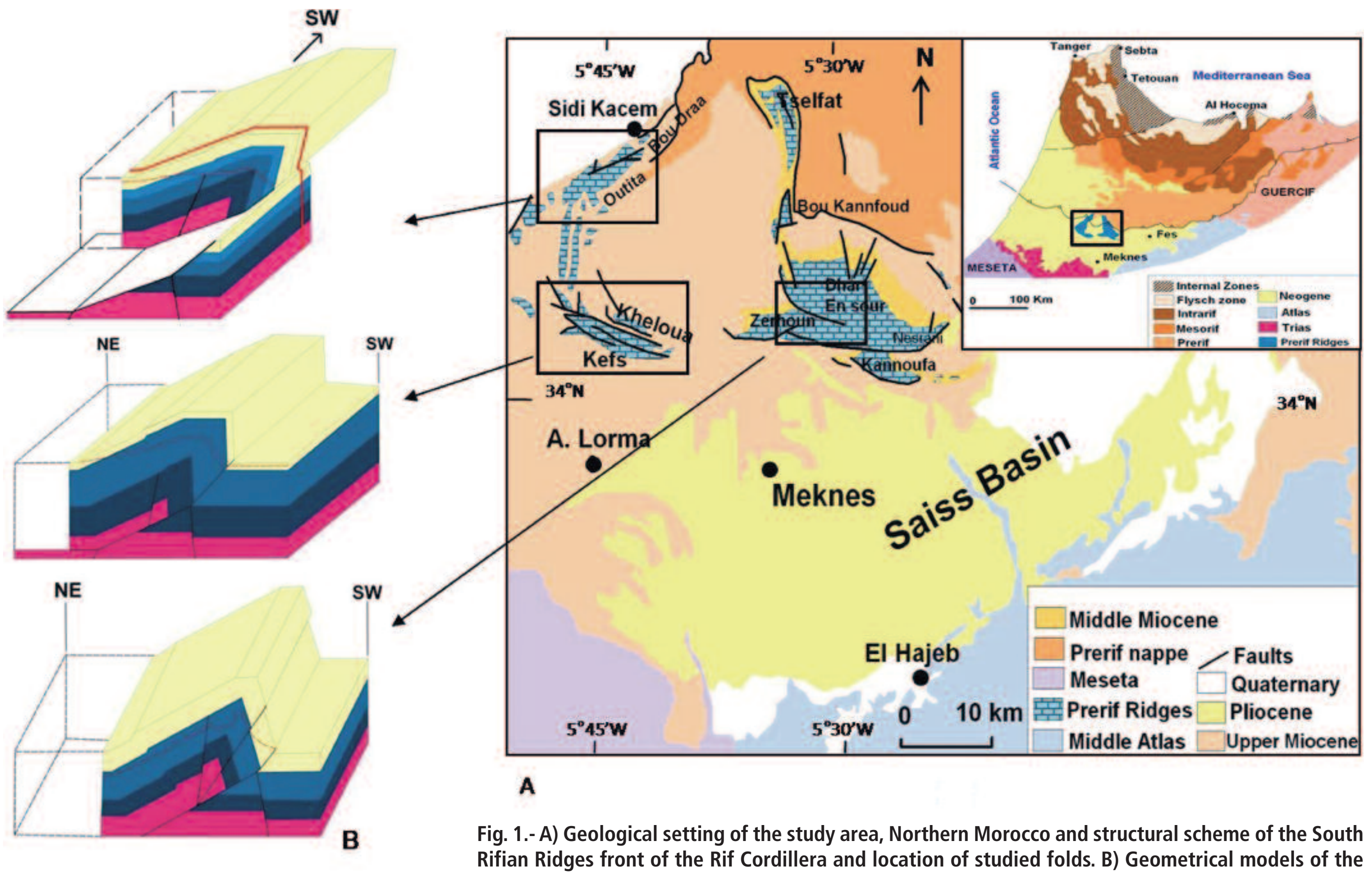

Fig. 1.- A) Geological setting of the study area, Northern Morocco and structural scheme of the South Rifian Ridges front of the Rif Cordillera and location of studied folds. B) Geometrical models of the studied structures. (See color version on the figure in the web page).

Fig. 1.- A) Situación geológica de la zona de estudio en el norte de Marruecos, esquema estructural del frente de las cadenas sur-rifeñas y localización de los pliegues estudiados. B) Modelos geométricos de las estructuras estudiadas. (ver versión en color en la página web).

Outita anticlines were analyzed in 16 sites, with 15 to 30 fractures per site. A total of three families are seen: oblique, axial and transverse fractures respect to the fold axes. The chronological relationships between the families are deduced from the geometry of these fractures and their relationships. Specifically in one site, at the western termination of J. Fert El Bir and Kefs anticlines (Figs. 2 and 3), the transverse fractures shifts in the same direction two successive oblique fractures and the axial fractures affect all the existing fractures in this site. Not surprisingly, different degree of fracture density is observed between the flanks of the same anticline, being higher in the southern flank (downstream d=12/m) than in the northern flank (upstream, d=6/m).

Kinematics model

Many studies have shown that discrete faults at depth are commonly linked to more distributed deformation, in particular folding, at higher levels. Forced folds are common where there is a distinct mechanical contrast between faulted basement and the detached sedimentary cover. The reconstruction of fold thrusts structures from three sectors (J. Fert El Bir, J. Kefs, J. Outita) implies a generalized *décollement* within the Triassic evaporites (Fig. 1B). The fault pattern developed during Miocene-Pliocene shortening is confronted with the theoretical results of kinematic and mechanical models (Suppe, 1985; Mercier and Mansy, 1995) developed above inherited normal faults. The obtained models from RAMP program (Mercier, 1995) permit to confirm the development of fold propagation faults in the three anticlines and to explain geometrical differences, existing between NE and SW flanks of Fert El Bir and Kefs anticlines and the SE and NW flancs of Outita Ridge.

Discussion and conclusion

Many authors have long been trying to find relationships between folding and fracturing (Riedel, 1929; Ramsay, 1967; Stearns, 1964; Stearns and Friedman, 1972). These models fix the location of the hinges at the beginning of the folding and imply that the rotation of the flanks develops the fold. Taking into consideration that hinges can migrate, the implications in terms of the fracture pattern are important Ahmadi, 2006). The analysis of the fracturing in different parts of Jebels Fert El Bir and Kefs anticlines shows a heterogeneous distribution of the fracturing, which at this stage of our study is not possible to interpret. However, the integration of the folding process with the development of fractures allows us to developing a kinematic model that combines the evolution of fault propagation fold to the development of fractures (Fig. 4). NE-SW compression during Lower Tortonian-Messinian times caused the detachment of the Meso-Cainozoic cover in the Triassic. This compression is accompanied by intense fracturing. A family containing oblique faults to the axis of the fold that grows as response to the stress field (σ_1 perpendicular to the fold, and σ_3 parallel to the fold and σ_2 vertical) is connected to the early stage of folding, with layer parallel shortening (LPS). After some level of shortening, a family, transverse faults, containing the fractures per-

Fig. 2.- Aspect of fractures measured in the western termination of the Fert El Bir anticline. (A) Directional opened fractures with a metric spacing, (B) Directional fracture opening amplified by the dissolution, (C) Different fractures and their chronology observed onto the stratification surface, (D) Aspect of the studied fractured limestones, metric strata are separated by false stylolitic joints and affected by vertical fractures.

Fig. 2.- Aspecto de las fracturas medidas en la terminación occidental del anticlinal de Fert El Bir. (A) fracturas direccionales abiertas con espaciado métrico, (B) amplificación de la apertura de una fractura direccional por disolución, (C) Familias de fracturas con la cronología relativa observada sobre el plano de estratificación, (D) aspecto de las calizas con fracturas, los estratos métricos están separados por juntas estilolíticas estratiformes y afectados por fracturas verticales.

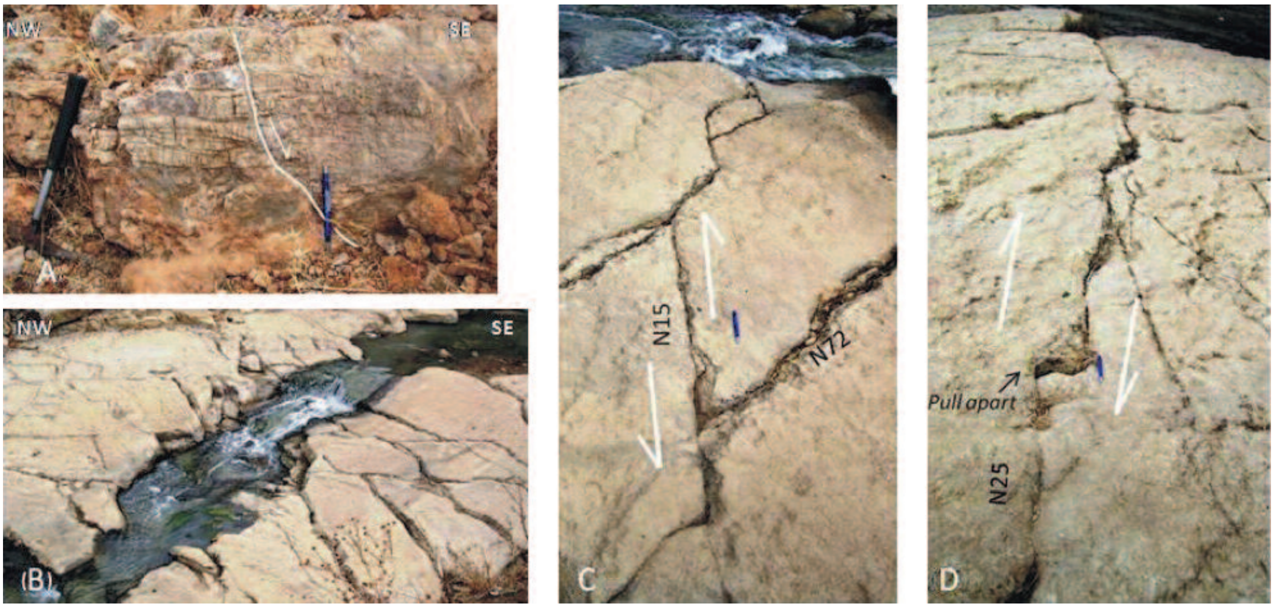

Fig. 3.- Aspect of analyzed fractures in different stations measured in the Kefs ridge (A) Geometry of a normal fault affecting brecciated stromatholitic limestones, (B) Network of fractures observed at the surface of a limestone strata near the source of My Yacoub El Hamma (C) Sinistral fracture N15 shifting fractures N72, (D) Dextral fracture N25 determining a small extensional jog.

Fig. 3.- Aspecto de las fracturas analizadas en distintas estaciones tomadas en la cadena de Kefs. (A) geometría de una falla normal afectando a calizas estromatolíticas brechificadas, (B) Sistema de fracturas observadas sobre un estrato de caliza cerca de la fuente de My Yacoub El Hamma (C) fractura con desplazamiento sinistro de dirección N015E desplazando a fracturas con orientación N072E, (D) fractura con desplazamiento dextro de dirección N025E formando un escalón extensional.

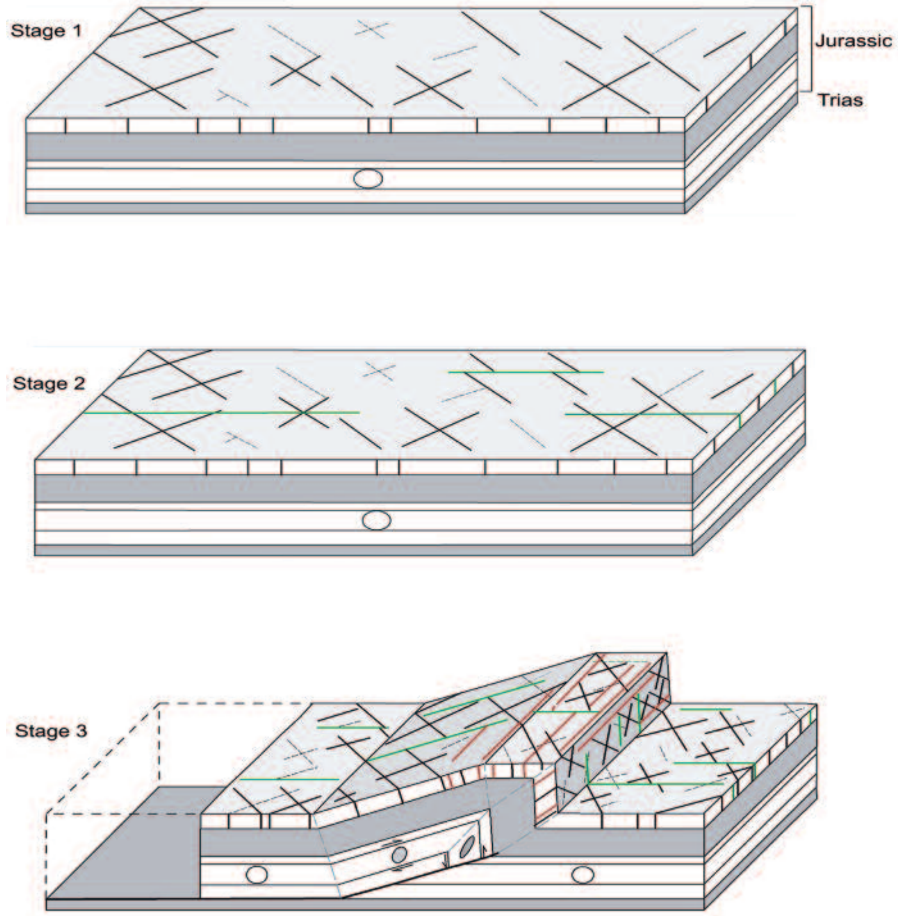

Fig. 4.- Explanatory model showing the relationship between folding and fracturing. Our hypothesis can explain the distribution of fracturing on the fold, while respecting the specific kinematics of fault propagation fold and the separation in time of fracturing and folding.

Fig. 4.- Modelo geométrico que explica las relaciones entre plegamiento y fracturación. La hipótesis planteada explica la distribución de fracturas en el pliegue, respetando la cinemática del pliegue de propagación de falla y el lapso de tiempo entre fracturación y plegamiento.

pendicular to the axis of the fold propagate parallel to σ_1 before the initiation of the anticlinal hinge. Finally, a third minor family of fractures parallel to fold is interpreted as the result of accommodating extension affecting the fold hinge (Stearns, 1964). This family corresponds to axial faults.

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