

Fault analysis and its relationship with karst structures affecting Lower Jurassic limestones in the Agourai plateau (Middle Atlas, Morocco)

Análisis de la fracturación y su relación con estructuras kársticas presentes en las calizas del Jurásico Inferior del plateau de Agourai (Atlas Medio, Marruecos)

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ABSTRACT

This study analyzes the fracture network at different scales in the Lower Jurassic limestones outcropping in the Agourai plateau, Middle Atlas, and their relationship with karst structures. This zone belongs to the Sub-Tabular Middle Atlas belt, called "Causses Moyen-Atlasiques". This area underwent a polyphased tectonic evolution, involving karst depressions aligned NE-SW parallel to the main faults. The approach is based on the fracturing analysis and the determination of relationships between tectonic events and the main karstic structures development, corresponding to aligned dolines forming important uvala systems. We analyze the karst distribution along the main faults affecting Liassic carbonates and we describe some karst sedimentary fill.

Key-words: Karst, fracturation, Liassic carbonates, Agourai Plateau, Morocco

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Introduction

Karst phenomena are well studied in the peri-mediterranean chains and are associated with the climate changes in this area from Cretaceous periods until Plio-Quaternary epoch (Soudet *et al.*, 1994; Molina *et al.*, 2000; Peybernes *et al.*, 2007; Tassy, 2012; Husson, 2013). In Morocco, many dolines are described in the Middle Atlas, particularly in the Ifrane area, where the main karstic depressions are important lakes, offering natural parks and ecological reserves. Despite the im-

portance of karst systems in the alimentation and drainage of groundwater aquifers, their knowledge in the Agourai plateau is still limited. This area constitutes the continuity towards the west of the tabular plateau of the Ifrane-El Hajeb area (Fig. 1), which has been the subject of important geological, hydrogeological and geomorphological studies.

Geological setting

In the Agourai Plateau, the Paleozoic basement is overlain by weakly deformed

RESUMEN

Este trabajo muestra un análisis de la fracturación a diferentes escalas que afecta a las calizas del Jurásico Inferior del plateau de Agourai, Atlas Medio. Esta zona pertenece al cinturón subhorizontal medio del Atlas y ha sufrido una evolución tectónica polifásica, con depresiones kársticas alineadas NE-SO paralelas a las fallas principales. Este estudio está basado en el análisis de la fracturación y la determinación de relaciones entre los eventos tectónicos y el desarrollo de las principales estructuras kársticas, que corresponden con dolinas alineadas formando sistemas de uvalas. Analizamos la distribución kárstica a lo largo de las fallas principales que afectan a las calizas del Lias y describimos los rellenos kársticos de algunas de ellas.

Palabras clave: karst, fracturación, carbonatos liásicos, plateau de Agourai, Marruecos

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times delimiting very narrow distensive structures corresponding to half-grabens, with tilted blocks recording continental Mio-Plio-Quaternary sedimentation (Bouya *et al.*, 2013a, b; Bouya, 2014).

Field geological data

Satellite image analysis and aeromagnetic data from the Agourai plateau show a NE-SW orientation for the main lineaments. These

structures are responsible for the recharge of aquifers within the Lower Jurassic limestones (Dauteuil *et al.*, 2016). However, the rose diagram of automatic extracted lineaments (see Fig. 3B) shows a maximum

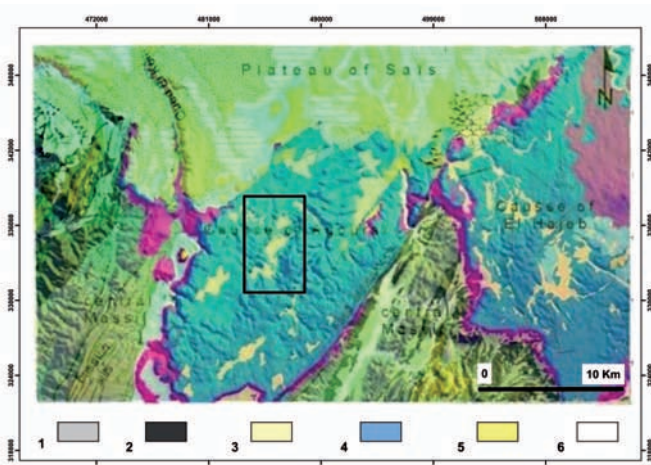


Fig. 1.- Geological map of the study area superimposed on the DEM. 1, 2. Paleozoic, 3. Triassic, 4. Jurassic, 5. Cenozoic, 6. Location of the karstic depressions. See color figure in the web.

Fig. 1.- Mapa geológica de la zona de estudio con el modelo digital del terreno sobrepuesto. 1, 2. Paleozoico, 3. Triásico, 4. Jurásico, 5. Cenozoico, 6. Localización de las depresiones kársticas. Ver figura en color en la web.

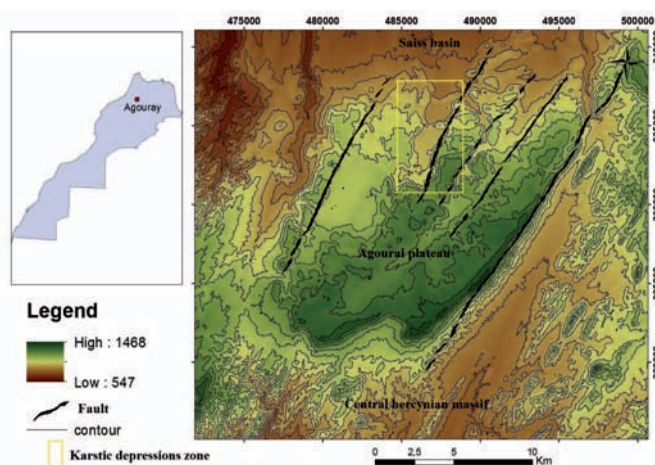


Fig. 2.- DEM of the Agourai plateau showing the main topographic depressions parallel to the NE-SW oriented faults. See color figure in the web.

Fig. 2.- Modelo digital del terreno del plateau de Agourai mostrando las depresiones topográficas principales paralelas a las fallas de orientación NE-SO. Ver figura en color en la web.

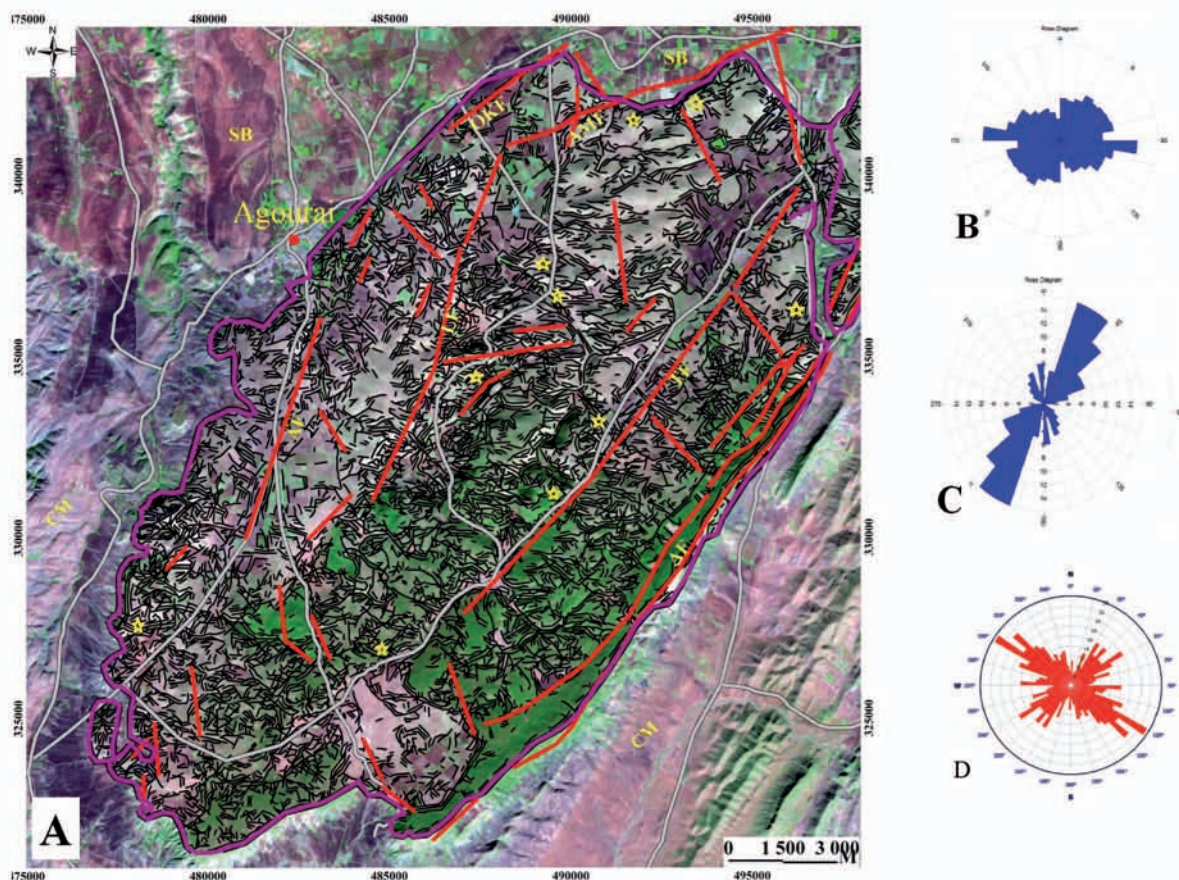


Fig. 3.- Lineaments in the Agourai plateau, overlapped on Sentinel-2A satellite image. A) Map of fractures in the Agourai plateau. B) Rose diagram of automatic extracted lineaments. C) Rose diagram of main faults extracted from lineament map. D) Rose diagram of fractures analyzed in different sites. See color figure in the web.

Fig. 3.- Lineamientos del plateau de Agourai sobrepuesto a la imagen satélite Sentinel-2A. A) mapa de fracturas en la plataforma. B) Diagrama de rosas de los lineamientos obtenidos de forma automática. C) Diagrama de rosa de las principales fallas. D) Diagrama de rosas de las fracturas analizadas en las distintas estaciones de análisis. Ver figura en color en la web.

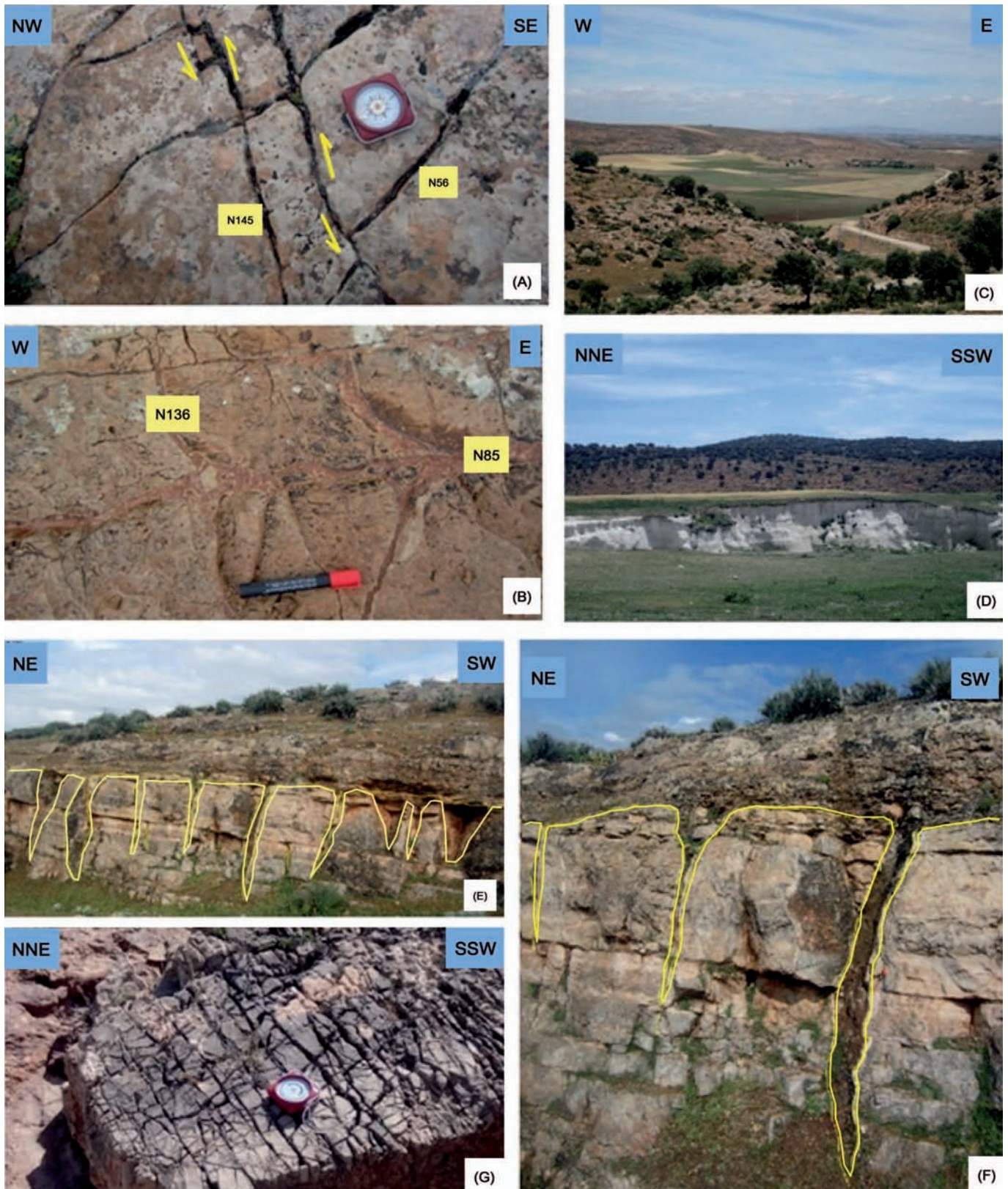


Fig. 4.- Photographs of the field geological structures analyzed in the study area. A) Open fractures oriented NE-SW, shifted by NW-SE fractures. B) Fractures filled by reddish detrital sediments. C) One of the main dolines conforming the polje of Agourai. D) Sedimentary filling of insoluble karstification residues from Liassic limestones within one of dolines. E) and F) Metric vertical tension gash filled with detrital reddish sediments. G) System of open fractures accentuated by the dissolution of limestones in the edge of a doline. See color figure in the web.

Fig. 4.-Fotografías de campo de estructuras geológicas analizadas en este estudio. A) Fracturas abiertas orientadas NE-SO afectadas por fracturas de orientación NO-SE. B) Fracturas rellenas por sedimentos detríticos rojizos. C) Una de las dolinas que forman el polje de Agourai. D) Relleno sedimentario de residuos insolubles de karstificación de de las calizas liásicas dentro de una de las dolinas. E) y F) Fractura tensional vertical rellena de sedimentos detríticos rojizos. G) Sistema de grietas abiertas amplificadas por la disolución de las calizas en el borde de una dolina. Ver figura en color en la web.

oriented E-W and two secondary maxima oriented NE-SW and NW-SE. On the other hand, the rose diagram relative to the main lineaments shows clearly the predominance of the NE-SW direction, compatible with mapped faults network in this area (Fig. 3C). However, the field measured fractures in about ten microtectonic stations show the predominance of the NW-SE direction, considered as the late fracture set, responsible for the Liasic aquifer drainage (Dauteuil *et al.*, 2016).

The systematic survey of about 360 fractures at ten stations along the plateau of Agourai (see yellow stars Fig. 3A) allowed us to determine three main directions, E-W, NE-SW and NW-SE (Fig. 3D). The latter appears to be the newest and most dominant.

In the central part of the Agourai plateau, the NE-SW karst depressions, described in this manuscript for the first time in this region, determine an uvala karst system separated by small carbonate corridors. These NE-SW aligned depressions can be qualified as a "polje karstic system".

The altitude difference between the edges and the uvala center can reach 80 to 100 m showing the importance of the karst collapse in this plateau.

Fracture analysis in the borders of the polje borders revealed the presence of brecciated limestone masses, with bedding dips oriented towards the center of the sub-circular depressions (Figs. 4 A, B and C). In some sites along the edges of the polje, vertical tension gashes filled with reddish detrital sediments appear. The walls of the gashes are coated with calcite indicating an intense rainwater circulation, responsible for the dissolution phenomena, which allowed these karsts to form (Figs. 4E, F and G).

The largest karst depression forms an uvala of about 800m in diameter. It is occupied in its lowest part (northern part) by two small sub-circular lakes, which characterize the karst landscape.

Discussion and conclusion

The Liasic carbonate formation is affected by different geological phenomena, corresponding to karstification, brecciation and mainly intense fracturation.

The Agourai plateau is affected by a main fault system oriented NE-SW, delimiting different blocks, elongated in the same direction.

It shows a regional slope of about 3% in the northern direction (towards the Saiss basin). These faults, which have controlled sedimentation during the Trias-Lias, appear to be ancient, inherited from the Hercynian basement, and have been reactivated during the Mesozoic extensional regime controlling the atlasic rifting (Charrière, 1990; Hinaje, 2004; Bouya, 2014). The intense fracturation affecting these Liasic limestones is related to extensional synrifting episodes, or to sedimentary brecciation following temporary emersions. Indeed, the study of fracturation in these carbonate formations revealed three directions: NE-SW, NW-SE and E-W. This fracturation was associated with the main phases of deformation that affected the Middle Atlas during the Cenozoic period (Hinaje, 2004; Amraoui, 2005; El Fellah Idrissi *et al.*, 2016).

In the mid part of the Agourai plateau, the karstic depressions have shaped its morphostructures. The main connected dolines determine an uvala that can even be considered as a karst polje extended in the NE-SW direction, parallel to the major regional faults.

In these doline edges, an intense fracturing and an important brecciation have been developed. This fact has determined the ruiniform limestones, characteristic of the karst landscape.

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