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# Fracture related-fold patterns analysis and hydrogeological implications: Insight from fault-propagation fold in Northwestern of Tunisia

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ABSTRACT

The spatial distribution of fracturing in hard rocks is extremely related to the structural profile and traduces the kinematic evolution. The quantitative and qualitative analysis of fracturing combined to GIS techniques seem to be primordial and efficient in geometric characterization of lineament's network and to reconstruct the relative timing and interaction of the folding and fracturing histories. Also a detailed study of the area geology, lithology, tectonics, is primordial for any hydrogeological study. For that purpose we used a structural approach that consist in comparison between fracture sets before and after unfolding completed by aerospace data and DEM generated from topographic map. The above methodology applied in this study carried out in J. Rebia located in Northwestern of Tunisia demonstrated the heterogeneity of fracturing network and his relation with the fold growth throught time and his importance on groundwater flow.



## 1. Introduction

Geological studies of fractured rocks in folds aim to determine firstly their mechanism of formation which allows the allocation of each fracture set to a specific stress field or geological setting. Secondly to develop methods for predicting the orientation, spatial density and connectivity of fractures where outcrops are sparse or absent that provide useful tools for solving practical problems related to groundwater or hydrocarbon flow in fractured aquifers and reservoirs. In the last decades of the 20st century, Several studies on the genetic relationships between fractures and tectonic history were carried out (De Sitter, 1959; Ramsay, 1967; Price and Cosgrove, 1990; Bahat, 1999; Konon, 2004; Peacock and Azzam, 2006; Marfil et al., 2005; De Joussineau et al., 2005; Guiton, 2001; Florez-Nino et al., 2005; Bellahsen et al., 2006; Ahmadhadi et al., 2007; Wennberg et al., 2007; Frizon de Lamotte et al., 1997; Saint-Bezar et al., 2002; Louis et al., 2003; Evans et al., 2003; Amrouch, 2010; Amrouch et al., 2010a; Khan, 2011). According to Bonnet et al. (2001), all consolidated subsurface rocks are fractured to some degree with a scale ranging from microcracks to crustal rifts. Fractured reservoirs characterized by secondary porosity generated through fracturing, continue to intrigue and challenge in the same way hydrogeologists (Faybishenko et al., 2013; Narasimhan, 2005; Bodin et al., 2007; Doherty, 2011; Masciopinto and Palmiotta, 2013; Caine and Tomusiak, 2003; Herrera and Garfias, 2013) and petroleum engineer (Bazalgette et al., 2010). GIS techniques are also useful (Sander, 2007; Al Saud, 2010; Corgne et al., 2010). The motivation for the study was to characterize surface heterogeneity at different scales. Specifically, the goal of this paper is to establish the link between fractures and a fault propagation fold tectonic history in a region of North Africa (Tunisia). i.e. Discriminate between pre, syn and post-fractures; secondly find the relationship between tectonics and groundwater circulation. i.e. Highlight features that control groundwater flow in fractured limestone and constitute a potential preferential pathways based on the continuity of geologic units and inferred fracturing distribution. The present study is based on a simple but powerful structural approach that consist in comparison between fracture sets before and after unfolding to understand the distribution of the fracture network and allocate each set to a fold development episode. Though the approach is described in some books, its applicability is not proven by examples in nature. Aerial photographs are primarily used for fracture mapping to define the location of major faults, subsequently, outcrop's are investigated in detail for the quantitative and qualitative analysis of fracture patterns. The works undertaken in this area are limited to those of Ould bagga (2003) as part of a study of the geodynamic evolution of the region Fernana–Ghardimaou. This study

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is carried out by applying a more detailed and comprehensive study of fracturing that characterizes the structural building and influence the flow of groundwater.

## 2. Methodology

### 2.1. Used approach

The study was carried out by a multiscale approach (Fig. 1) combining data from aerospace, digital and those in the field. The use of such multiscale methodology was in order to overcome two major problems including scarcity of fracture surfaces exposed in relief and there's no sufficient mirrors faults data to conduct a detailed microtectonic study and connect fracturing to stress.

The study of fracturing begins by harvesting Data supplied and their treatment in a quantitative and qualitative aspect. The fissure system was studied in outcrops located on the hinge, the northern flank and the two endings Periclinal.

### 2.2. Data collection and treatment

The method used for data acquisition of fracturing as described in many studies (Singhal and Gupta, 1999); is to find representative structural surfaces for the characterization of fracturing (medium and minor fractures) and then counting joints and major paraclases observed. For each station fracturing, an imaginary line (scan line) is drawn perpendicular to the direction of each of fractures. Then any fracture intersecting this line is included in the sample. The attitude (strike and dip) of each surface observation is noted. Of each fracture, the different parameters measured and/or observed are dipping direction filling opening and inter-fractural distance. In light of the record sheets set fractures, directional rose diagrams by families of 10° were made with stereographic projections software (GEOrient software).

Fractures striking either perpendicular or parallel to bedding strike are not affected by rotation of bedding to remove the dip and may be interpreted as occurring during any stage of fold growth. The fracture data were unfolded using the rotation necessary to bring the average bedding back to a horizontal attitude. Diagrams of 'folded' and 'unfolded' fracture sets will be presented in order to discuss their chronological relationship with folding. Relative timing of multiple fracture sets was assessed by using cutting/abutting relationships at the outcrop (Potts and Reddy, 1999).

The different parameters of harvested land fractures represent their current state (post tectonics) and unfolding rose diagrams obtained according to the fold axis (N40°) (Fig. 8) allowed us to classify fractures related the kinematics of the fold into pre, syn and post fractures. Indeed, the fractures that have kept the same direction before and after unfolding are post folding while those who changed direction following the unfolding are pre-or syn-folding fractures.

Aerial photographs dating from 1961 and 1998s, August, at scale (1/25,000) (Fig. 8) were analyzed in 3-D with a stereoscope and the Digital Elevation Model (Fig. 5) interpretation was completed using the different structures and textures. The interpretation of these sensing images, using a stereoscope, has to recognize and map the structural lineaments of the study area (Fig. 8). Validation is performed by field surveys. Therefore, the interpretation of aerial photographs allowed us to have an overview of the structure and faults.

A critical analysis combining all results (Fig. 8), i.e. photo-interpretation of DEM (Fig. 3) and aerial photographs, and geological elements (already known from maps and new ones identified in the field) was made.

## 3. Location and geologic setting of study area

The study area is located in the Northwestern part of Tunisia (Fig. 2). Its a well individualized fold belt that axis trending in the same atlases' strike (NE–SW). Geologically this area is extremely interesting since it outcrops in a transitional zone between a stable and autochthonous domain materialized by the Jurassic

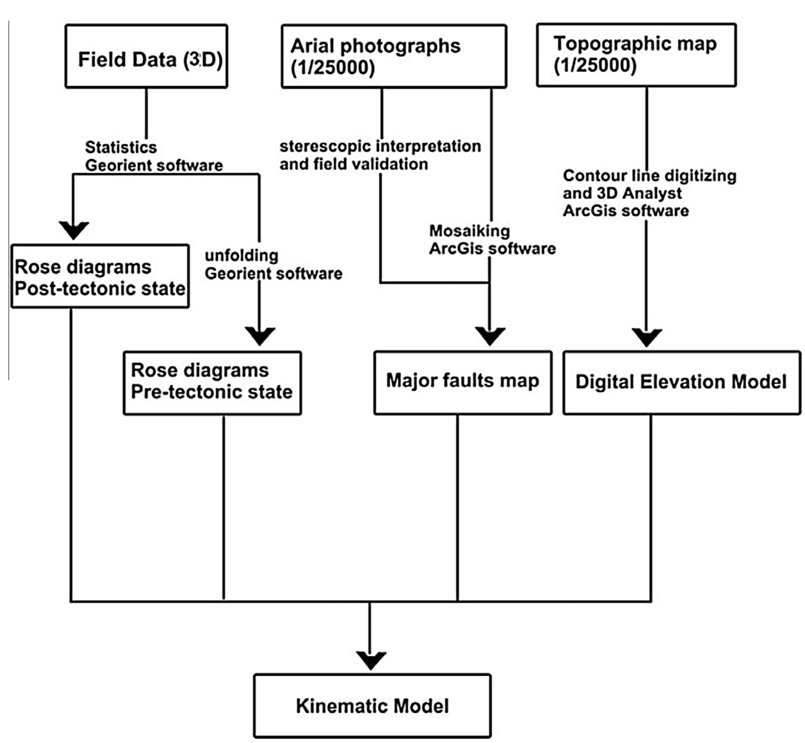


**Fig. 1.** Flow chart showing the used methodology.

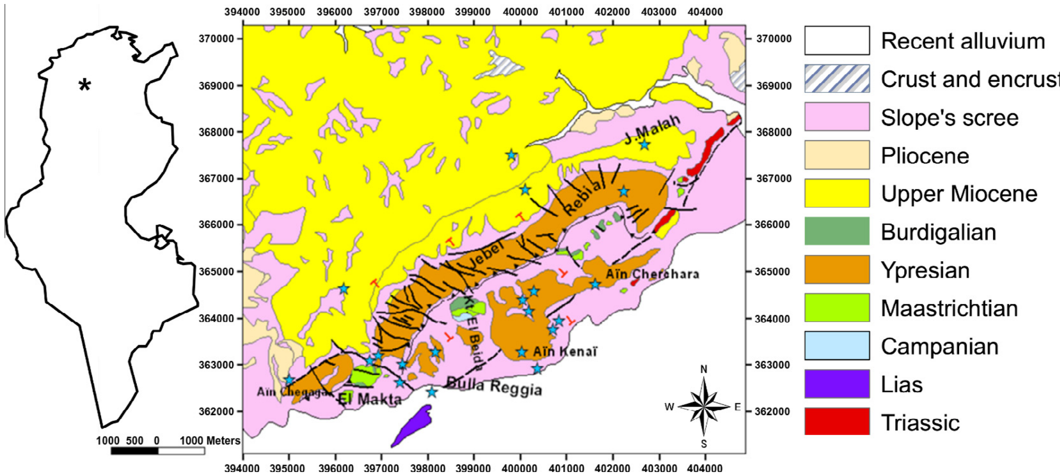


**Fig. 2.** Location of the study area and regional structural mapping.

Hairech's outcropping and another one, which is tectonically active and mainly characterized by folds, faults and thrust sheets.

A previous structural study of the region (Ould Bagga, 2003) highlights its kinematic evolution and describes Jebel Rebia as a Fault-propagation fold characterized by sub-horizontal hinge that forms, taking advantage of the meridional fault, a abrupt cliff, and a northern steep limb (Fig. 6). Outcropping materials are from Mesozoic to Quaternary areas, with detritical and carbonate rocks (Fig. 3).

The investigated geological formation in this study consist of fractured Ypresian limestone rocks (Fig. 2). Ould Bagga (2003) indicates that their thickness is about 500 m and composed mainly of massive limestone with interbedded marl levels at bottom (see Fig. 4).

The ridge tectono-sedimentary model conceptualized by Ould Bagga (2003) (Fig. 5) shows that block's tilting at the SE of the Ras El-Hairech Koran accident and the halokinetic movement at its base, lie behind a raised southeast ridge field that evolved during Paleogene in a ridge area of no deposition or intensive erosion. As for the SW, there is a deep subsiding area confining globigerine-rich limestones and Paleocene marls series.

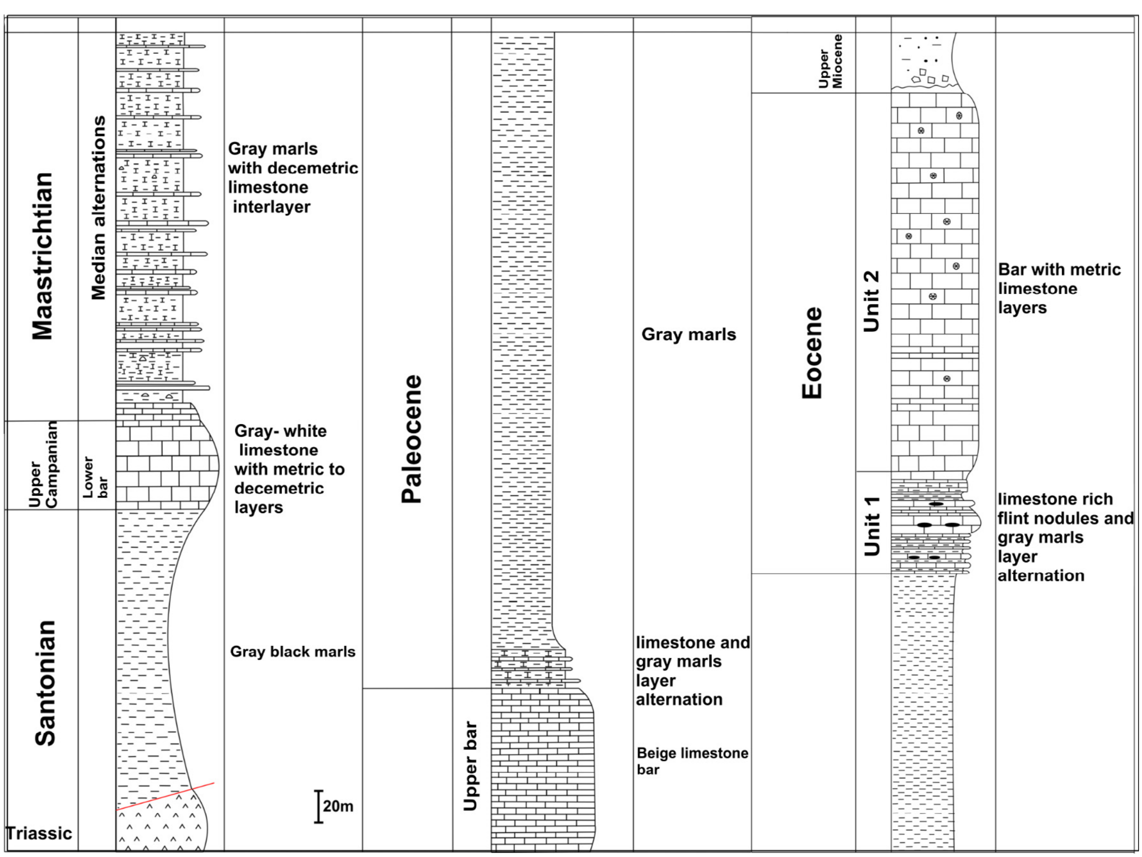


**Fig. 3.** Stratigraphic succession in J. Rebia anticline area.

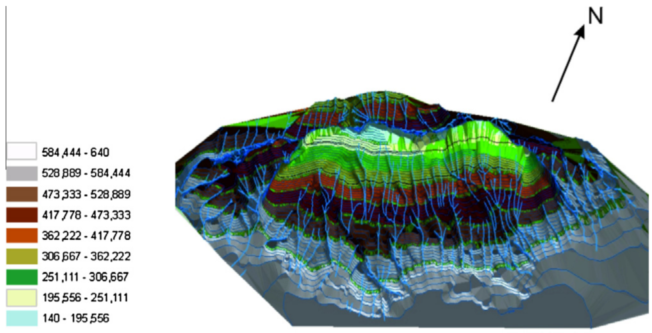


**Fig. 4.** Digital elevation model (DEM) of J. Rebia (3D view).

The series of the basin, subsequently shortened thrusts the ridge series. This is facilitated by the ductile Paleocene marls layer serving as a flat and a ramp that begins at the junction of the décollement level and the Hairech Ras El-Koran accident (Fig. 5).

The genesis of this fold is attached to a transpressive regime (Upper Miocene), guided by the sliding of Ras El-Hairech Koran NE–SW accidents, post-thrust. The belt is subsequently segmented by axial faults with NE–SW trough and NW–SE strike-slip faults, which confers to it the current structure and narrowband layout at the outcrop.

During its development, the Southwest compartment of J. Rebia (Fig. 6) was blocked by the autochthonous Jurassic limestones. This is reflected in the field by a backthrust in its Southwest compartment.

## 4. Results and discussion

### 4.1. Structural analysis

The analysis of aerial photography at 1/25,000 scale, covering the sector, reveals the lineaments mostly oriented NW–SE. This direction is systematically the most noticeable from these photos. These fractures are the hectometric strike-slip faults trending NW–SE, founded on the field.

Moreover, examination of DEM allowed us to conclude the predominance of NW–SE faults with appearance of other subvertical to NE–SW faults to the south and the north of the structure.

At large-scale, two main fault sets were identified in the field: A first set of overall NE–SW (N35°–N65°) at average dip of 40° and they are synsedementary inherited axial faults (Ould Bagga, 2003) that trend SW–NE. These faults border the belt in his Northern and Southern part and are formed during the stages of deformation prior to folding. A second set oriented roughly NW–SE (from N105 to N155) with vertical to subvertical dip (70°W to 90°) with a sinister slide. These faults seem most persistent and most dense; they are strike-slip faults, crosscutting the first set. These faults can be interpreted as a post folding structures. On other third one trends EW, but is less important compared to two previous sets.

Globally, in measurements undertaken in the field, we found that there are four sets of fractures (NS, EW, NE–SW and NW–SE). One set measured in a station is not necessarily found in other. This could be dependent on the position were the measurement was done in the fold.

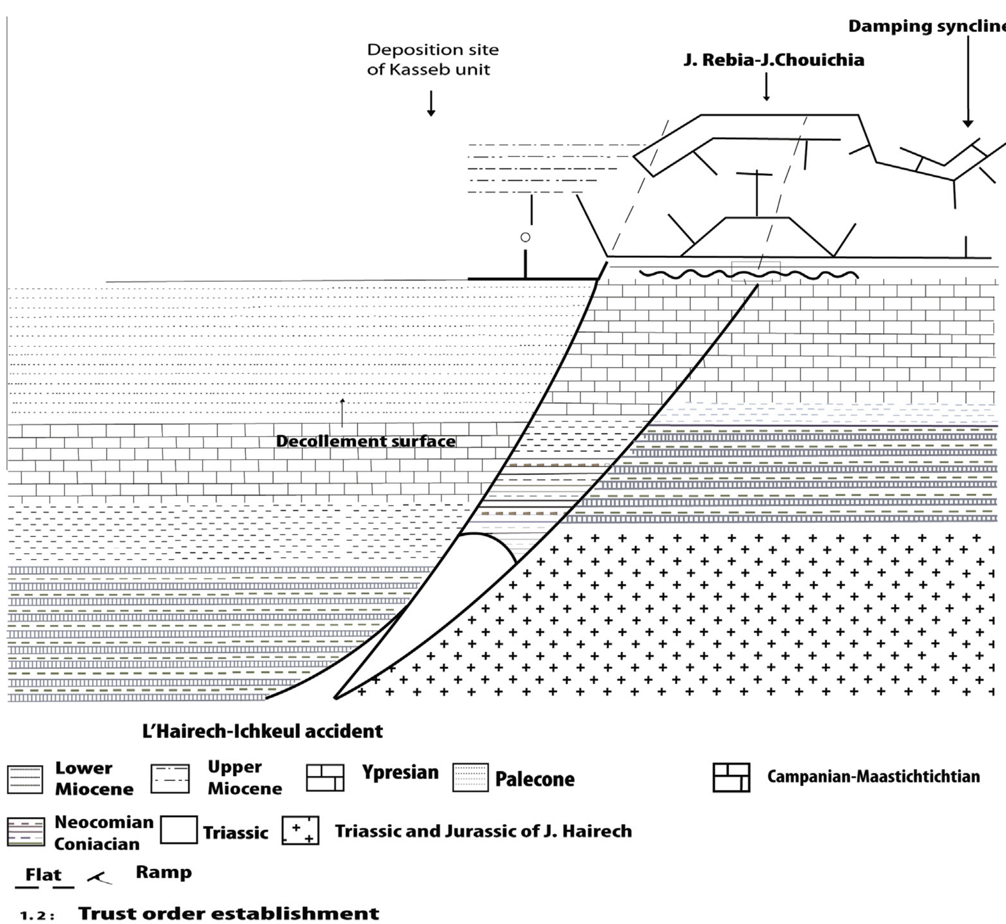


**Fig. 5.** Genesis mode of J. Rebia anticlinal (Ould Bagga, 2003).

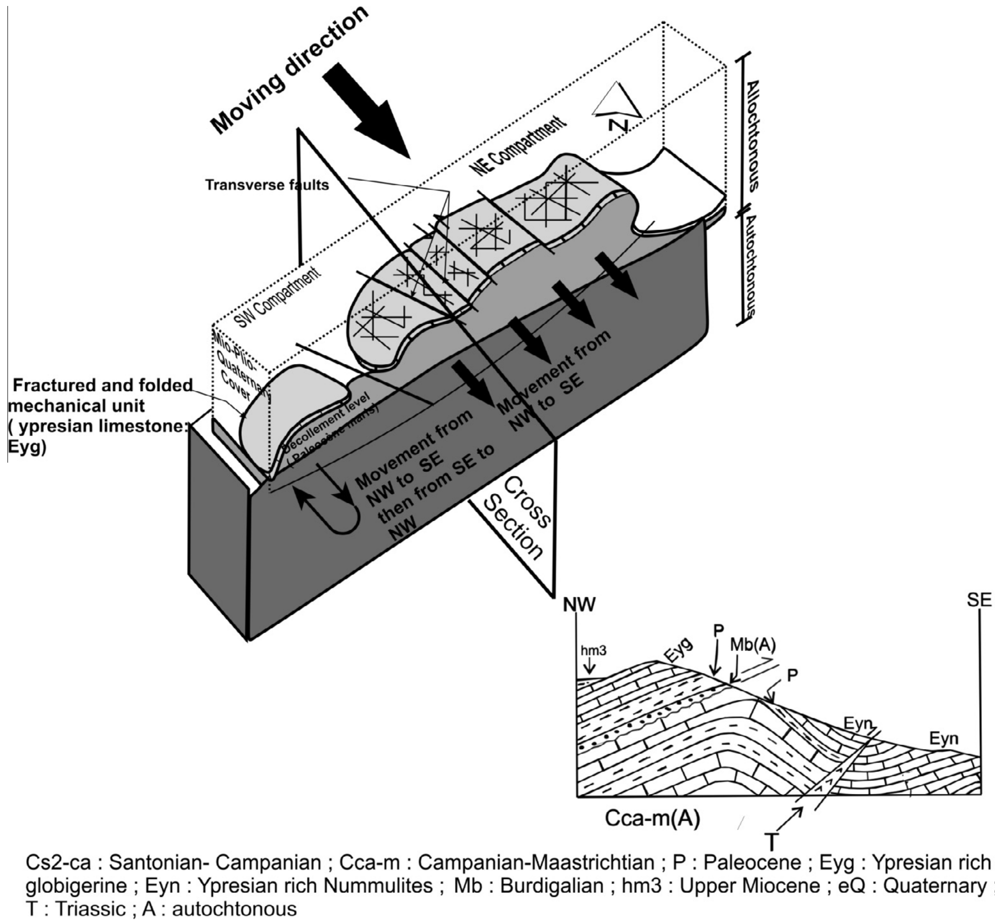


**Fig. 6.** Block diagram showing the geometry of the two compartments of J. Rebia.

As described above, the fractures sets are determined regarding their occurrence as pre-, syn-, and post-tilting/folding products based on their geometric relationships with tilted bedding (Fig. 7).

Our analyses show that sets wich trend N–S, NW–SE and NE–SW (observed in most sites) remain parallel even after unfolding, therefore we can conclude that are linked to the same tectonic phase and can be interpreted as post-folding fractures or early-folding sets.

The fourth set that trend E–W is not observed in all sites so its statistically less abundant than the three above sets. This set change strike after unfolding, its probably a pre or syn-folding set.

During fold growth, deformation was mainly accommodated by early-folding sets, wich are related to the tardive shortening (late stage fold tightening). In addition, massive appearance of limestone in the backlimb and layers dip relatively important (30°) makes it vulnerable to an internal deformation which indices are quite common and evidenced by rights relay. The inter-layers slip, main factor in simple shear in fault-propagation folds according to Suppe and Medwedeff (1990) and favored by the marly intercalations in basal end of the Eocene Series of J. Rebia, can serve also for deformation accommodation.

The classical schema of fold-related fractures is unclear in some of our sites, because of the irregular local direction of fold movement, and their overall progressive change from NW–SE to SE–NW in the southwest compartment (Fig. 6). It is rare that all of the orientations are present, or that the conjugate fractures sets are present in equal intensities. Occasionally, one of the sets is entirely absent. Analysis of the chronological development of fractures (including faults) with respect to regional folding (or tilting) allows their categorization them into four stages: pre-, syn-, early-syn, and late to post-folding (Fig. 8).

### 4.2. Hydrogelogical implications

Fractures are the major path for fluids to flow (Priest, 1993; Berkowitz, 2002; Narasimhan, 2005) and play an important role in the hydrodynamics of rock masses by building connective networks that channel flow (Pollard and Aydin, 1988; Matthai and Belayneh, 2004). Fractures control outcrop-scale fluidflow in carbonate rocks (Rawnsley et al., 2007; Gale et al., 2010; Larsen et al., 2010; Amoruso et al., 2013). Moreover, the geomechanical conditions under which these form influence the overall pattern and connectivity structures they display, also, timing and nature of fracturing can affect regional subsurface fluid flow (Mayer and Sharp, 1998).

In addition to joints systems, and fracture networks associated with faults, fractures networks formed during folding, can present good potential fractured aquifers (Tremblay, 2007).

The large-scale movement of fluids through rocks of relatively low matrix permeability may occur in diffuse fracture patterns in folds (Travé et al., 2000; Fischer et al., 2009). This low permeability can be overcome by the formation and connection of (early and synfolding) fractures facilitating fluid migration (e.g., Fischer et al., 2009).

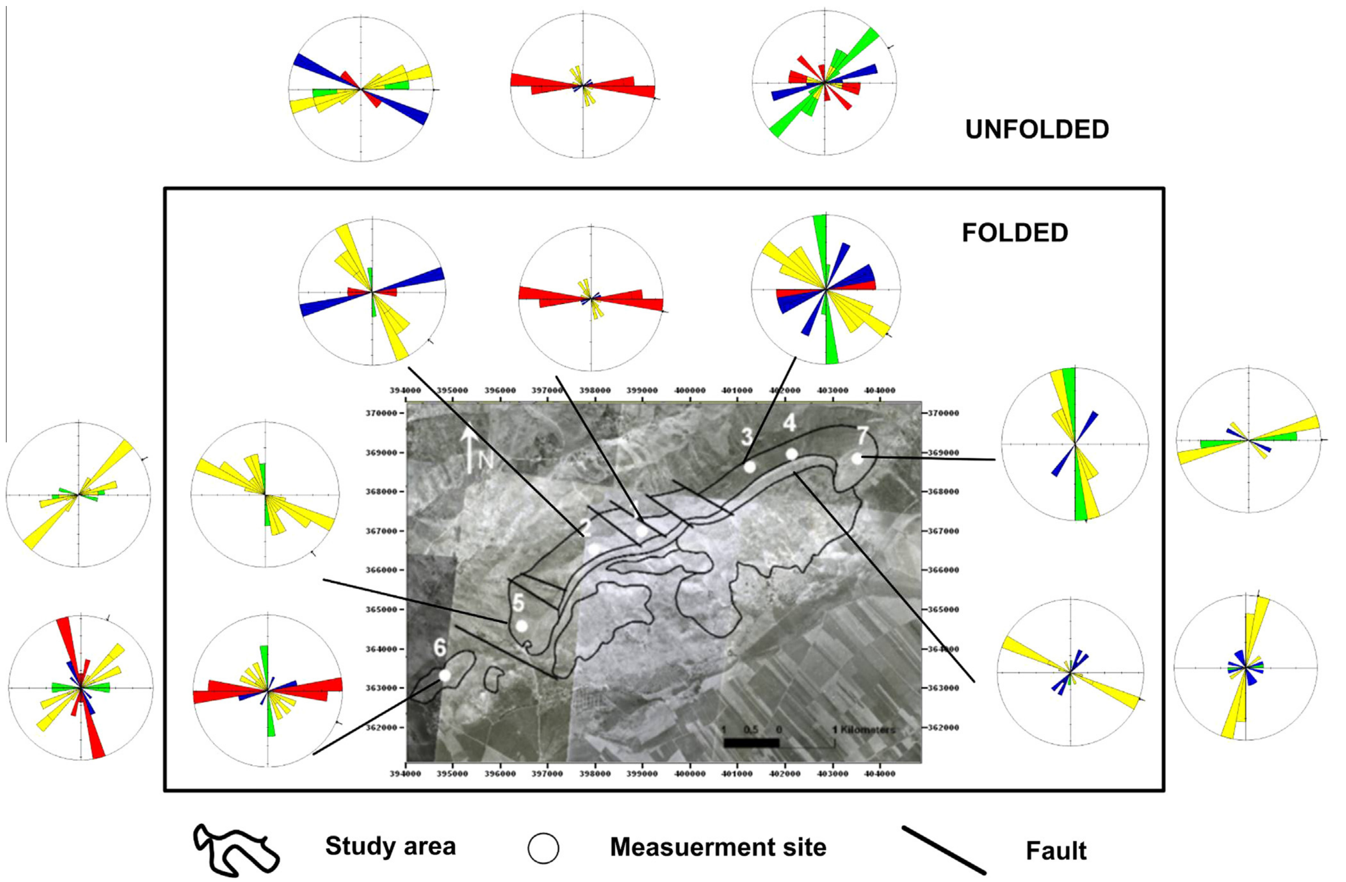


**Fig. 7.** Results of fracture analysis. For each site of fracture measurements, the rosediagram inside the rectangle shows raw fracture data, while the rosediagram outside the rectangle shows unfolded fracture data.

## 4.3. Case study

The organization of fracturing and its nature (opening, filling) influences greatly the permeability in fractured reservoirs. More dense network of fractures is the better permeability of the reservoir formation. This be able to be explained by the proliferation of channels and the increased probability of interaction between them (and hence connectivity). Superimposing several directional families amplifies permeability and provides good connectivity (Bazalgette, 2004). It is important to note that hectometric and kilometric faults can be both as drains or barriers to flow of fluids. This is inherent to their orientation to field stress. Indeed, they can then gape and act as drain or close and oppose the circulation by sealing.

In the case of J. Rebia, dominant major faults are parallel to the direction of shortening overall NW–SE, which promotes their opening allowing them to conduct water to deeper levels.

The field survey showed that connectivity in these networks is important. The flow is preferably in a direction perpendicular or substantially oblique to the fold axis. Late reopening of fractures, such as the northern branch of the Ras El-Hairech Koran, can also provide a preferential flow direction, especially since they are associated with synthetic faults. This ensures good connectivity between fractures and promotes a flow parallel to the plane of the main fault, in the intersection of these fractures direction. Some fractures were replayed several times during the phases that have succeeded, either in compression or distension as demonstrated by striated faults plans.

This fault system SW–NE with polyphase movement seems very suitable for groundwater flow and remobilization of water resources.

NW–SE faults are characterized by large opening and subvertical to vertical dip, also they are filled by breccia and clastic elements. Moreover fractures near increase the anisotropy and heterogeneity of the environment are of these discontinuities hydrogeologically interesting. They collect water and facilitate the infiltration and hence the groundwater recharge.

Going up to the aquifer scale, many carbonate aquifers discharge their waters through one or a few high-flow-rate springs.

In this study we try to establish a link between fracturing and hydrodynamic through spring yield.

Gaugings carried out at different dates show that the monthly yield of Ain Kenai spring forming the outlet of the of limestone syncline, varies from 2 l/s during the summer at 10 l/s during winter. It is clear that changes in this spring rates correlates positively with rainfall (Fig. 9). A flood is observed with a flow rate of 10 l/s in response to intense precipitation. During the summer period the low flow rates are explained by the evaporation of water before reaching the groundwater and small amounts of precipitation. The slight shift observed during the winter could be explained by the transit time of the water to reach the groundwater.

## 4.4. Groundwater flow

Measures of layers dips on the top the structure allow us to conclude that its axis (N40°) dips to the SW. Geomorphology of

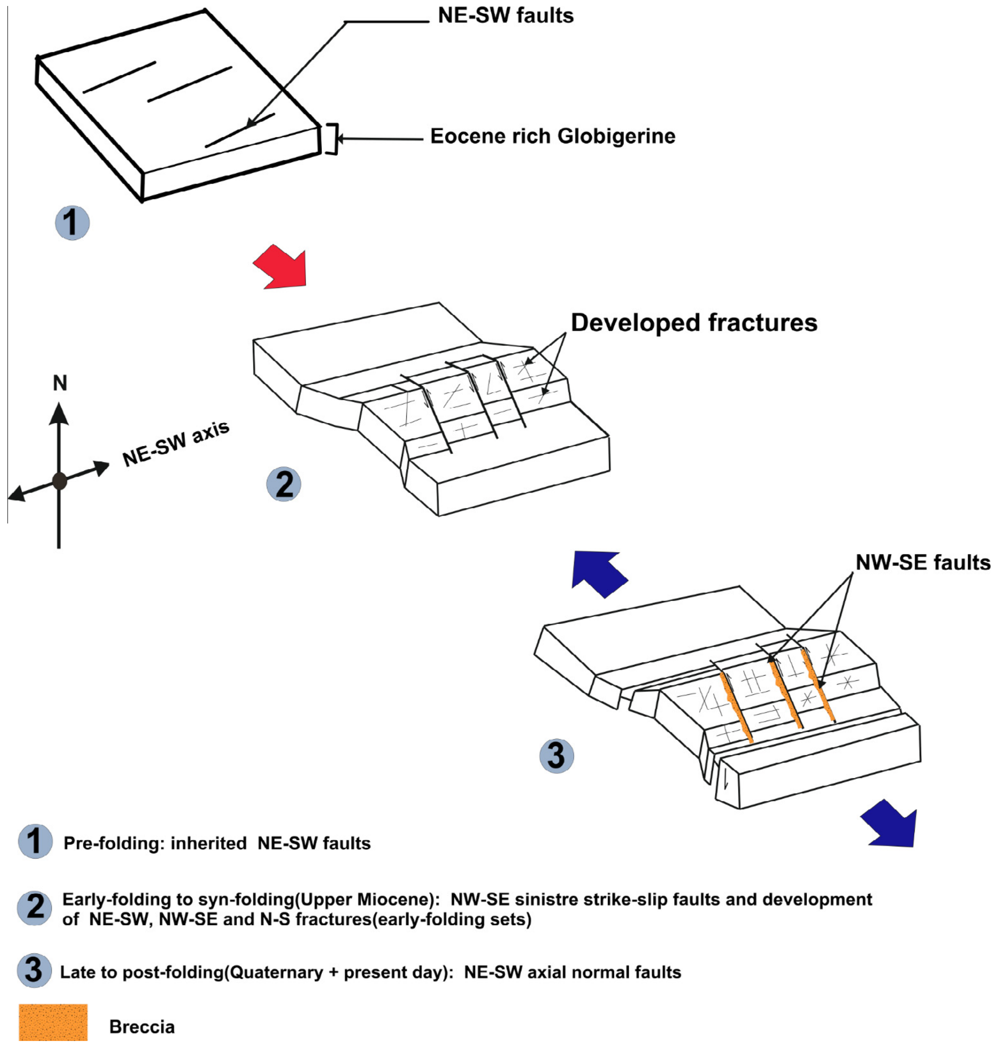


**Fig. 8.** Scenario showing the main fracturing stages and segmentation of J. Rebia.

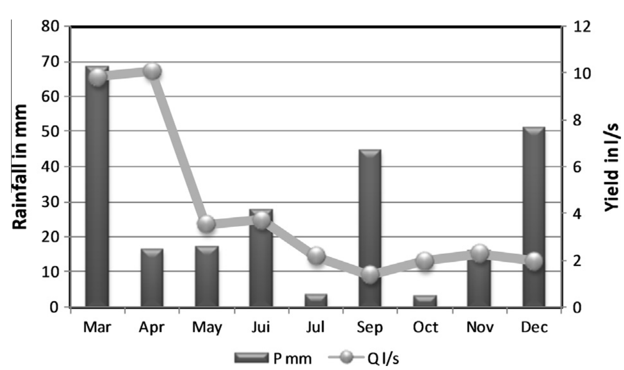


**Fig. 9.** Relationship between monthly rainfall at Jendouba station and monthly yields of Ain Kenai in 1987/1988 and 1988/1989.

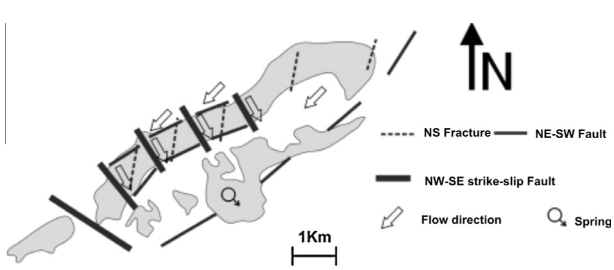


**Fig. 10.** Groundwater flow in J. Rebia limestones.

antiforms ripples succession and synforms in sector helps hollow to collect surface water and to drain towards the center of the synclinal structure designed by the southern fault.

The surface flow is to the south in favor of fractures affecting the allochthonous unit, while joints provide horizontal flow towards the SW (Fig. 10).

## 5. Conclusion

Fracture analyses in folded strata within the Rebia Folded Belt in the Northwestern part of Tunisia provide information on the fracturing distribution associated with fold growth. The fold began its evolution in favor of inherited normal faults. Accommodation of curvature is made thanks to the sliding inter-beds and early-folding fractures, while oblique strike slip faults to the axis of the fold helped its compartmentalization. This study completed the previous work in more detail and served as a support to enhance the relationship between fracturing and local hydrodynamics. Fracture network as demonstrated is hydrogelogically important.

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