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Active tectonics and drainage evolution in the Tunisian Atlas driven by interaction between crustal shortening and mantle dynamics

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Abstract

Active tectonics in North Africa are fundamentally driven by NW-SE directed slow convergence between the Nubia and Eurasia plates, leading to a region of thrust and strike-slip faulting. In this paper, we analyse the morphometric characteristics of the northern Tunisia sector. We aim to identify unknown active tectonic structures, and to further understand the mechanisms driving the drainage evolution in this region. The interpretation of morphometric data was ground-truthed with field data. Our analysis indicates that recent fluvial captures have been the main factor driving fluvial network reorganization in NE Tunisia. The Medjerda River has increased its drainage area during the Quaternary by capturing adjacent axial valleys to the north and south of its drainage divide. These captures are probably driven by the gradual uplift of adjacent axial valleys by reverse/oblique faults or associated folds like El Alia-Teboursouk and Dkhila faults. Our fieldwork found that these faults cut Holocene sediments thus showing recent fault activity. The growth and stabilization of the axial Medjerda River, contrary to the natural transverse drainage development of mature orogens, might be caused by a combination of crustal shortening structures and mantle dynamic processes. The Medjerda River flows SW-NE from the South Atlantic dextral transfer zone to the regional topographic low defined by the Gulf of Gabes and the Straits of Sicily, which in turn, may be influenced by the underlying Tunisian slab in the region.

1 Introduction

Crustal thickening related to plate convergence and associated shortening structures, together with upper-mantle flow that produces dynamic topography, influence drainage systems at active plate boundaries (Braun, 2010; Husson et al., 2012). Convergence in active collisional

continental plate boundaries favours the development of transverse drainages that route sediments from the orogenic wedge towards the foreland basin system (DeCelles and Giles, 1996). In these orogenic regions the interplay between active tectonic structures like thrusts, antiformal folds or lateral ramps greatly determine the geometry of the drainage pattern, especially the relationship between transverse and axial drainage systems (e.g. Hirst and Nichols, 1986; Burbank et al., 1996; Jones, 2004). The natural evolution of rivers draining mountain belts is to develop earlier axial drainages parallel to local tectonic structures that evolve to transverse drainages following the main topographic gradient in the latter stages (Babault et al., 2012). Relative small-scale dynamic topography is especially important in regions with narrow underlying lithospheric slabs like the western Mediterranean (Faccenna and Becker, 2010; Faccenna et al., 2014; Petit et al., 2015; Booth-Rea et al., 2018). Geodynamic mechanisms like slab pull, slab tearing, slab delamination or flow in the upper mantle exert an important influence on local topography that can be largely independent of the crustal structure (e.g. Missenard et al., 2006; Gogus and Pysklywec, 2008; Mancilla et al., 2015). Moreover, other factors like lithology, inherited geological features or fluvial captures can play an important role in drainage organization (e.g. Harvey and Wells, 1987; Stokes, 2008; Giaconia et al., 2012a).

The interaction between these different factors can result in anomalous drainage patterns with regard to those expected considering the direction of regional convergence. This might occur in Tunisia, where the main catchment draining the orogenic wedge is the Medjerda River that runs SW to NE for 400 km from eastern Algeria to the Gulf of Tunis, perpendicular to the regional NW-SE convergence (Fig. 1). Recent seismic tomography has shown the presence in the mantle of a slab under Tunisia that could contribute to dynamic topography in the region

(Fichtner and Villaseñor, 2015). Booth-Rea et al. (2018) have also highlighted the importance of the slab tearing and the STEP boundary in the evolution of northern Tunisia.

The slow NW-SE convergence rate in Tunisia, of ~ 0.5 cm/yr, (McClusky et al., 2003; Goes et al., 2004) (Fig. 1) results in low to moderate magnitude seismicity (Gueddiche et al., 1998). Instrumental seismicity in the period from 1920 to 2010 registered magnitudes ranging from M_w 2 to 5.5 (Ksentini and Romhdane, 2014) (Fig. 1). However, historical records describing the destruction of Roman and Arabic settlements support stronger seismic events (e.g. Ambraseys, 1962; Bahrouni et al., 2014). The most important ones were in Utica in 412 A.D., with coseismic ground fractures and aftershocks that lasted for one week; in Tunis in 856 A.D., with $\sim 45,000$ victims and a moment magnitude (M_w) estimated of 6.8; and in Tunis in 1758 A.D., with several houses destroyed and thousands of victims (Ksentini and Romhdane, 2011; 2014).

Relief analysis based in drainage network metrics is a good tool to detect and characterize active tectonic structures in regions with low to moderate tectonic activity (e.g. Keller and Pinter, 2002; Molin et al., 2004; Pedrera et al., 2009; Pérez-Peña et al., 2010; Azañón et al., 2012). Recent studies have suggested that river network systems can take moderate to long periods (10^4 - 10^7 yr) to reach their final equilibrium profiles, i.e. steady-state conditions (Goren et al., 2014). However, rates of response increase exponentially from equilibrium and, therefore, gross deviation from the equilibrium conditions must reflect relatively recent events (Brookfield, 1998; Pérez-Peña et al., 2009a). The combination of different morphotectonic indices allows differentiating uplifting from subsiding regions at different scales. This approach together with a geomorphological study and field groundtruthing helps to discriminate between different mechanisms that may influence topography and associated drainage networks development (e.g.

Bull and McFadden, 1977; Azor et al., 2002; Giaconia et al., 2012a; 2012b). These methods have been applied before in Tunisia with the same goal, but regarding a local scale and not taking into account the whole northern Tunisian region (Ben Hassen et al., 2014; Slama et al., 2015; Mimouni et al., 2016; Rabii et al., 2016; Sadrette et al., 2016).

Figure 1. Seismicity distribution and present-day GPS motions of the western Mediterranean region. Blue circles have been taken from the ISC-GEM catalog (<http://www.isc.ac.uk/iscgem/>) and red circles from the ISC (<http://www.isc.ac.uk/iscbulletin/>). The location of the study area and the Medjerda River are indicated in the Figure. Horizontal velocities (with 95% error ellipses) given with respect to the Eurasian plate (modified from Serpelloni et al, 2007)) along the Nubia Eurasia boundary in western Mediterranean.

The main goal of this work is twofold: first, we aim to evaluate the interplay between different mechanisms that may influence the drainage network in northern Tunisia at different scales like upper mantle structure, horizontal shortening related structures, lithology or fluvial captures; and, secondly, to determine the active tectonic structures that form the Nubia-Eurasia boundary in this complex region, where present-day tectonics have been scarcely studied. For this, we have applied a quantitative morphometric analysis to the topography of northern Tunisia, accompanied by fieldwork, to determine the evolution of the Medjerda River fluvial network and its relation to tectonic structures. Following this approach, we mapped some of the possible main active faults in the studied region and surveyed potential capture sites, abandoned

fluvial channels, and fluvial terraces, looking for evidence of recent deformation like striated pebbles in river terraces.

2 Geological setting

The tectonic evolution of Tunisia shares common features with the mountain belts that surround the western Mediterranean, having accommodated the shortening related to the northward subduction of the Nubian plate under Eurasia since the Palaeogene (Wortel and Spakman, 2000; Faccenna et al., 2005; Booth-Rea et al., 2007; van Hinsbergen et al., 2014). However, recent full-wave inversion mantle tomography shows that the subducted Thethyan mantle lithosphere is segmented into different slabs underlying the Betics and Rif, the Algerian Tell, Tunisia, and Calabria (Fichtner and Villaseñor, 2015). Thus, each one of these belts has developed its own particular tectonic features, having undergone an independent tectonic evolution at some stage, thanks to the development of Subduction Transform Edge Propagator faults (STEP faults) (Govers and Wortel, 2005) like the Nekor and Crevillente faults in the Gibraltar arc (Mancilla et al., 2015) or structures to the south of the Tyrrhenian sea, like the Malta escarpment in the Calabrian arc (e.g. Argnani and Bonazzi, 2005; Soumaya et al., 2015).

The images of mantle slabs under Algeria and Tunisia suggest that they are detached from the overlying lithosphere at ~150 km depth (Fichtner and Villaseñor, 2015), although, under SE Tunisia the slab may extend to shallower regions and be connected to the Nubia plate as indicated by the presence of a high-velocity reflector imaged by refraction seismics in the mantle at 87 km depth under central Tunisia, slightly north of the southern Atlasic deformation front (Research Group for Lithospheric Structure in Tunisia, 1992). In Algeria slab rupture occurred during the Middle Miocene producing post-collisional K-rich calc-alkaline magmatism dated at 17 Ma (Abbassene et al., 2016). Meanwhile, in Tunisia the rupture from the Calabrian

slab, and the possible concomitant delamination of the African continental mantle lithosphere (Roure et al., 2012) is constrained by shoshonitic rhyodacites dated between 14-8 Ma in northern Tunisia and Galite island and alkali basalts extruded at 8-6 Ma (Savelli, 2002; Decrée et al., 2014). Slab delamination and retreat in Tunisia was subparallel to the NW-SE convergence between Nubia and Eurasia (Roure et al., 2012), probably contributing to the southward propagation of the Tunisian Atlas belt, with an important component of left-lateral transpression (Melki et al., 2011). NW-SE plate convergence continues at the present day (Soumaya et al., 2015) producing the tectonic inversion of many extensional structures developed by slab rollback or slab rupture dynamics, including the Algero-balearic and Tyrrhenian basins (e.g. Kherroubi et al., 2009; Billi et al., 2011; Giaconia et al., 2015; Rabii et al., 2018).

Northern Tunisia can be divided in the Tellian and the Atlas structural domains. The Tellian domain is characterized by flysch sediments of the Tethys Sea, with ages ranging from upper Cretaceous to Tertiary. These sediments normally crop out in the northern part of Tunisia thrust over the Tunisian Atlas domain (Fig. 2). The underlying Atlas rocks are derived from the northern Maghreb palaeomargin, with ages ranging from Triassic to Neogene (Melki et al., 2010; 2011). After Paleozoic extensional and rifting periods, the alpine orogeny started in the upper Cretaceous, due to the convergence between the African and Eurasian plates. This resulted in the generation of the mountain belt of northern Africa and the uplift of the Atlas, Apennines and Betics (Melki et al., 2012). In Tunisia these domains form the eastern prolongation of the mountain belt of northern Africa and the Atlas mountain range (Lamotte et al., 2000).

Sediment units spanning from the Mesozoic to the present-day occur in northern Tunisia (Fig. 2) (Melki et al., 2012). Gypsum, clays, carbonates and multicolor sandy facies with chaotical structures characterise Triassic units. These units often act as a detachment level of the thrust faults and present tectonic contacts with other formations in northern Tunisia. Jurassic sedimentary units are characterized by calcareous facies with some marly intercalations typical of deep-sea environments. Cretaceous sediments crop out mainly in northern Tunisia and consist of fossiliferous marls and clays with micritic limestone intercalations and sandy and quartzitic recurrences. These sediments were deposited in a subsiding marine environment.

Paleocene-Eocene sediments crop out in northern Tunisia and are represented by a monotonous brown argillaceous package. These argillaceous deposits present a lithological

succession with marls and limestone intercalations. Eocene sediments are formed by carbonate series of early Eocene age that produce positive reliefs above other softer units. Oligocene-Aquitania rocks form the northwestern succession of the Numidian Flysch. This formation is characterized by allochthonous turbidites that include clays at the base and sandstones and shales at the top. The southeastern basins of northern Tunisia contain sandy, clayey and carbonated facies indicating a shallow marine to fluvial environment.

During the Miocene, limestone bars were deposited above conglomerate facies in the Gulf of Tunis, indicating the beginning of a transgression period. Following strata are composed of clays, silts and occasionally of sandy limestones at the base and marls and salts at the top. Deep-marine green clays rich in microfauna were deposited in eastern Tunisia during the late Miocene, capped by regressive continental series at the top. Coastal and offshore areas are represented by a thick series composed of clays, sandstones and lignite alternations characterizing an internal shelf depositional environment.

During the Pliocene, marine sediments were deposited along the eastern coast of Tunisia with argillaceous and sandy-fossiliferous series. On the other hand, early Pliocene continental clays and sandstones occur towards the west. The late Pliocene is essentially represented by sandy series.

Quaternary sediments mostly occur along current valleys of northern Tunisia and are fluvial terraces, alluvial fans or colluvial covers together with lacustrine sediments in some particular regions (Fig. 2). Some of the Plio-Quaternary fluvial terraces are found abandoned and raised from their original location and usually show rounded pebbles with poor cementation. Bannour and Bonvallot (1988) proposed that Quaternary diapiric dynamics deformed and raised up some alluvial terraces of the Medjerda River, nevertheless, the geometry and distribution of

folds occurs strongly controlled by pre-existing structures what suggest that Quaternary contractional deformations does not promote diapirism (Masrouhi et al., 2014). These Quaternary deposits are represented by continental facies composed of gravels, clays, sands and silts. Marine and eolian deposits crop out also along the northern and northeastern littoral of Tunisia.

2.2 Structural setting

The main structures in northern Tunisia are large sinistral-reverse NE-SW faults and their associated folds (Fig. 3). These faults use the Triassic evaporites as a detachment level and produce positive reliefs following the general NE-SW regional topographic trend (Hlaïem, 1999). The main faults of northern Tunisia from West to East are: Cap Serrat-Gardimaou, Ras El Korane-Thibar, El Alia-Teboursouk, Tunis-Ellès and Zaghouan (Fig. 3) (Melki et al., 2012). Moreover, there are also conjugate dextral and normal NW-SE faults (Zargouni, 1978; Melki et al., 2010). The phase of present-day active deformation in northern Tunisia started in the Upper Pliocene, related to the northwestward motion of Nubia relative to Eurasia (Fig. 1). This process is uplifting the Atlas and reactivating preexisting faults (McClusky et al., 2003; Goes et al., 2004). WNW-ESE faults are reactivated with reverse dextral motion, while NE-SW ones are reactivated with pure to oblique reverse motion. This reactivation formed new folds with NE-SW axes (Mejri et al., 2010; Alyahyaoui and Zouari, 2014; Zouaghi et al., 2010). Moreover, the southwestern boundary of the Tunisian Atlas is delineated by large NW-SE dextral structures like the Gafsa and Tozeur-Negrine faults (Zargouni and Ruhland, 1981; Ben Hassen et al., 2014).

Concerning the large-scale crustal structure of Tunisia, the Moho discontinuity deepens towards the south, from depths of approximately 21 km near the northern coastline to maximum depths of 37 km at the southern deformation front. However, in the NE-SW direction the Moho

discontinuity depth is rather uniform (Research Group for Lithospheric Structure in Tunisia, 1992).

2.3 Geomorphological setting

The main geomorphological features of northern Tunisia are NE-SW oriented ranges with their respective associated valleys (Fig. 3). In some locations, the drainage network shows rectangular patterns and river deflections that may reflect major lithological or tectonic boundaries. The Medjerda River is the largest catchment of Tunisia and drains an area of $\sim 23,340 \text{ km}^2$. It runs as an axial valley 400 km from eastern Algeria to the Gulf of Tunis in a SW-NE direction, parallel to the main faults and folds of northern Tunisia. The source of the Medjerda River lies in Algeria at 1300 m in a semi-arid region of the Atlas system (Delile et al., 2015). According to Faust et al. (2004), the current climate corresponds to the Mediterranean subtropics (with a transition from Mediterranean semiarid, corresponding to the southern Algerian region, to semihumid conditions, corresponding to the northern Tunisian region). Furthermore, although morphodynamic changes through the floodplain sediments of the Medjerda have been described (and have been related to North Atlantic Bond events), the Quaternary sedimentation of the river seems to have taken place under rather stable circumstances allowing to develop well-stratified layer sequences (Faust et al., 2004; Zielhofer and Faust, 2008). The tributaries of the Medjerda River drain areas ranging from 54 to $2,564 \text{ km}^2$ running from 8.5 to 163 km long and show two preferential orthogonal flow directions, NE-SW and NW-SE. Clearly and entirely transverse catchments to the main geological grain are short and only developed across the present deformation front, draining to the Gulf of Hammamet (Fig. 3).

The topography of Tunisia is relatively smooth, with heights below 1,385 m and gentle slopes of about 6°. The highest elevations in the region occur at the Medjerda headwaters in eastern Algeria with heights up to 1770 m. The landscapes are mainly fluvial, with rivers with meandering shapes and locally incised reaches. Large lacustrine zones mostly occur towards the east and in an east-west line at the northern edge of the Saharan platform where the lowest point in Tunisia (-17 m) occurs coinciding with the salt lake of Shatt al Gharsah.

Figure 3. Tectonic sketch of northern Tunisia with the main shortening structures in the region and the drainage pattern. The black polygon shows the study zone. The red box shows the zone surveyed in the field (Figure 14). Tectonic structures include data from Melki et al, (2012), Bahrouni et al, (2014) and Rabaute and Chamot-Rooke (2015), as well as our own data.

3 Methodology

We have applied different morphometric analyses to characterize the recent tectonic activity of northern Tunisia. First, we computed the drainage network and selected the main

basins with their trunk channels from a Digital Elevation Model (DEM) of 30 m pixel resolution. For each basin, we computed the normalized longitudinal profile, the hypsometric curve, the area-slope distribution and the normalized steepness index (ksn). We also studied the first-order vertical steep knickpoints within the study area. This morphometric analysis was accompanied by fieldwork to examine morphometric anomalies, wind gap locations and deformation features in Quaternary sediments to determine the possible relation between morphometry anomalies and active tectonic structures or fluvial captures.

3.1 Drainage network extraction and selection of drainage basins

To perform the morphometric analysis, we used a DEM of the Shuttle Radar Topography Mission (SRTM) from the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA). This DEM provides a grid of 1 arc-second of resolution (approximately 30 m), a linear vertical relative height error of less than 10 m and a circular relative geolocation error of less than 15 m (Farr et al., 2007). To extract the drainage network for the morphometric analysis we used the D8 flow algorithm (O'Callaghan and Mark, 1984) and delineated channels with an area threshold of 3 km².

3.2 River normalized profiles

Rivers in equilibrium condition develop a typical concave-shaped profile, with higher gradients in source areas and gentler near the mouth. This shape can be interpreted as the long-term resulting balance between internal forces that produce surface uplift and external processes that tend to erode it away. Any deviation of this equilibrium profile suggests active uplift or lithological changes of the riverbed (Brookfield, 1998; Pérez-Peña et al., 2009a; Matoš et al., 2016). Analysis of river longitudinal profiles has been used to discern the role of lithology and

tectonic uplift as controlling factors (Brookfield, 1998; Pérez-Peña et al., 2009a; Kirby and Whipple, 2012; Giaconia et al., 2012a). However, the comparison of longitudinal profiles from rivers with different lengths and gradients can be intricate. Demoulin (1998) proposed the representation of river longitudinal profiles in a normalized form. These profiles show relative distances and elevations in a range from 0 to 1, by normalizing with the total length and relative elevation of each river. This representation allows the comparison of rivers with different lengths and gradients (Demoulin, 1998; Ruskiczay-Rüdiger et al., 2009; Castillo et al., 2013; Matoš et al., 2016). This normalized form also allows the extraction of geomorphic metrics to evaluate profile concavity. The concavity factor (C_f) is defined as the percent area of the triangle between the river profile and the line connecting mouth and source. The normalized distance from head to the point where the maximum concavity (C_{max}) is reached is defined as $MaxL$.

In this work we computed the normalized profiles with their related indexes (C_f , C_{max} and $MaxL$) for the trunk channels of the selected drainage basins. These parameters enable analysis of the equilibrium stage of selected rivers, i.e. how these rivers move closer to or away from their graded profiles. Ideally, normalized river profiles with high C_f and low $MaxL$ (rivers with maximum concavities close to the river source) are characteristic for concave profiles that are approaching their equilibrium stages, while convex profiles with low C_f are characteristic for areas where tectonic uplift is dominant (Demoulin, 1998; Ruskiczay-Rüdiger et al. 2009; Castillo et al., 2013; Matoš et al., 2014; 2016).

3.3 Chanel steepness index

Bedrock rivers depict a power relation between channel slope and discharge (approximated by up-stream area) (Equation 1):

Eq. 1

$$\frac{dz}{dx} = \frac{U}{K A^m} \left(\frac{U}{K} \right)^{1/n}$$

where dz/dx is the local channel slope, U is the rock uplift rate, K is an erodibility coefficient, A is drainage area, and m and n are empirical constants (Seidl and Dietrich, 1992; Howard et al., 1994; Perron and Royden, 2013). In this equation, $(U/K)^{1/n}$ is referred to as channel steepness (ks) and n/m as the concavity index (θ). The concavity index typically varies in a narrow range (~ 0.4 - 0.6) and it is thought to be relatively insensitive to differences in rock uplift rate and bedrock lithology (Kirby and Whipple, 2012; Whipple et al., 2013). However, the steepness index is directly related to uplift-rate (U) and erodibility (K), thus making this index a useful metric in landscape analysis (Whipple and Tucker, 1999; Whipple, 2004; Kirby and Whipple, 2012; Ferrater et al., 2015; Matoš et al., 2016; Andreani and Gloaguen, 2016).

One of the most popular approaches to estimate the channel steepness is through the integration of both sides of equation 1, which leads to the equation 2 (Perron and Royden, 2013):

Eq. 2

$$x = \frac{A_0}{K} \left(\frac{U}{K} \right)^{1/n}$$

With:

Eq. 3

$$A_0 = \left(\frac{U}{K} \right)^{m/n}$$

Equation 2 has a linear form that relates a new horizontal coordinate () with the profile elevation (Perron and Royden, 2013; Royden and Perron, 2013), the slope of this line will be the ksn index (A_0 is normally taken as 1 m^2 to remove dimensionality).

In this paper, we used the analytical solution proposed by Perron and Royden (2013) to calculate chi values at pixel level by calculating the cumulative sum of $(A_0/A_{(x)})^{m/n}$ upstream for

a fixed concavity (θ_{ref}), and multiplying by the distance between two neighboring pixels. The Chi index, in spite of having units of meters, can present large-scale variations by using different θ_{ref} values. A general value of 0.45 is often used as a convenient value for large drainage basins (Willett et al., 2014; Yang et al., 2015), however better constrained results can be achieved by using a m/n value that minimizes dispersion in chi plots (Perron and Royden, 2013; Willett et al., 2014; Goren et al., 2014).

In order to select the best reference concavity for the study area, we performed a sensitivity analysis based in previous works (Perron and Royden, 2013; Willett et al., 2014; Goren et al., 2014). The slope of a chi-elevation plot is defined as $(U/K A_0^m)^{1/n}$, thus profiles that present changes in uplift (U) or lithology (K) along their lengths will present different slopes. Therefore, instead of looking for the best m/n value using the individual profiles of the main channels, we selected the value that minimizes data-dispersion in Chi-elevation space for the whole network of the Medjerda basin, following Yang et al. (2015). To account for this dispersion, we plotted all possible values of chi-elevation from Medjerda basin (i.e. all pixels belonging to the network) and computed the R^2 of their linear regression for different m/n values from 0 to 1 (Fig. 4). The reference m/n value of 0.3 produces the best fit (Fig. 4), i.e. the minimum dispersion between the different channels of the basin. To illustrate this, Fig. 5 depicts the chi profiles with their R^2 for m/n values of 0.2, 0.3 and 0.4, showing that the chi plot with $m/n = 0.3$ minimizes dispersion.

Figure 4. Sensitivity analysis of m/n for the Medjerda basin. We have computed the R^2 for the chi and elevation of all the points of the basin computed with different m/n values (from 0 to 1 with a step of 0.01). The reference concavity that produces the higher correlation and thus minimum dispersion is 0.3.

Figure 5. Chi plots for all the tributaries of the Medjerda River computed with m/n values of 0.2, 0.3 and 0.4. R^2 values of the sensitivity analysis are indicated.

Our approach estimates the ksn index along a channel by linear regressions in Chi-elevation space in two different ways. First, local values of ksn index are calculated for all the pixels of the whole drainage network by taking linear regressions with wide windows of 15 pixels down and upstream (or more with especially noisy profiles, Fig. 6). This approach to calculate gradients (slope and ksn), despite slightly lowering the absolute values, minimizes profile noise and retains profile knickpoints (Fig. 6). The local ksn values have been used to derive ksn profiles for each channel and a ksn map for the whole study area. Alongside the regression slope (gradients), we also obtain R^2 values in order to remove those with low linearity (high noise). To generate the ksn map, points with very high values due to reservoirs or DEM errors have also been removed. Secondly, regional ksn trends have been derived by completing linear regressions on Chi profiles. These regressions depict mean ksn trends, and also allow location of slope break knickpoints between segments with very different regional ksn.

Figure 6. Effect of estimating profile gradients (slope and ksn) with regression using wide windows centred in each pixel. Note that the 25 points window (up and downstream) has slightly lower absolute values but minimizes noise at the same time to better define knickpoints.

3.4 Knickpoint analysis

Abrupt slope changes or changes in slope trends along river longitudinal profiles are commonly known as knickpoints. They are defined as the “fluvial portion of the transient boundary between adjusting and relict topography” (Crosby and Whipple, 2006). Knickpoints in erosive systems form in response to a perturbation (tectonic activity, lithological changes, capture processes, etc.) that produces a migrating boundary that separates upstream regions that remain unaffected from downstream regions that are adjusting to the new conditions.

As we calculated the local ksn values for each pixel of the main channels, we can derive ksn plots for them (Fig. 7). Knickpoints will be depicted in these profiles as “peaks”, making also possible to record their absolute values of ksn. However, as these ksn profiles can show noise, we would combine the logarithmic area-slope plot with these new derived ksn profiles. As a general rule, we don't consider any knickpoint that is not clearly depicted in the area-slope logarithmic plots. In the case of noisy data, we increase the number of points to derive local ksn and slopes (Fig. 6). In the case of segments with a high regional ksn value, the knickpoints are only be considered if its value is clearly higher than the regional ksn of the segment (Fig. 7). We only consider knickpoints with ksn values greater than 2.5 and classify them into three different classes; i) minor or local knickpoints (ksn between 2.5 and 4.5), ii) moderate knickpoints (ksn between 4.5 and 6.5), and iii) major knickpoints (ksn over 6.5).

Figure 7. Four different profiles used in this work; a) longitudinal profile (S1), b) Chi-elevation profile (S2), c) area-slope logarithmic plot (S4) and d) ksn profile (S5). Derived knickpoints are shown in the four profiles. Regressed ksn segments derived in the chi plots are also shown in the ksn profile. Only knickpoints clearly identified in the area-slope plots are defined (note the first peak in the ksn profile that is located in the colluvial part of the profile has been discarded).

3.5 Hypsometric curves

Hypsometry studies the mass distribution within a drainage basin in terms of area-elevation (Strahler, 1952), and can be evaluated by the hypsometric curve and the hypsometric integral (HI). The hypsometric curve describes the distribution of cumulative relative areas vs relative elevations and the HI is a measure of the relative area below the curve (Strahler, 1952; Ohmori, 1993; Keller and Pinter, 2002). The shape of this curve correlates with the stage of geomorphologic evolution of a particular drainage basin and, therefore, provides useful information about its erosional stage (Strahler, 1952; Ohmori, 1993; Pérez-Peña et al., 2009b).

Basins in a young stage of development will depict convex-shaped curves, mature basins will yield S-shaped curves, and intensively eroded basins close to the peneplain stage will draw highly concave curves (Strahler, 1952; Ohmori, 1993; Pérez-Peña et al., 2009b). In active mountain ranges hypsometric curves will evolve over time and will inform about the interplay between tectonic forces that tend to maintain convex curves and erosional processes that push hypsometric curves to mature and concave shapes (Pérez-Peña et al., 2009b; Ferrater, et al., 2015; Matoš et al., 2016). River capture processes will produce an increase of convexity from mouth to head, due to the advance of the new incision wave by headward erosion (Pérez-Peña et al., 2009b; Ferrater et al., 2015). In this work we extracted the hypsometric curves for the selected basin with the aid of CalHypso ArcGIS Tool and the data from the 30 m DEM (Pérez-Peña et al., 2009b).

3.6 Fieldwork

The morphometric analysis was completed and checked with a field campaign focusing on the locations with indications of recent tectonics. First, we analyzed some of the faults with potential activity indicated by the morphometric analysis. We studied their kinematics, measured striae and dips, and searched for young sediments affected by these faults. Secondly, we studied Pliocene to Pleistocene river terraces closer to the faults, in order to evaluate their location with respect to the actual rivers. Thereby, we focus on the identification of terraces in abandoned fluvial channels likely related to river captures. We analyzed striated pebbles in those abandoned terraces by measuring dip, direction and sense of movement (when possible) of striae and performed a stress analysis with the T-Tecto software. These structural markers preserve information on the stresses that their host rocks have undergone (Ruano and Galindo-Zaldívar, 2004). Finally, we looked for paleoseismological indicators like coseismic cracks, etc. (e.g.

Papanikolau et al., 2015). Due to the large extent of the field area analyzed by the morphometric analysis, we restricted the fieldwork to a limited area where we ground-truthed our geomorphic interpretation.

4 Results

4.1 River normalized profiles

We extracted the normalized longitudinal profiles for the 33 main basins and the Medjerda River main channel (Fig. 8 and S1). We analyzed the Medjerda River separately due to its length and greater area. Concavities (C_f) vary in a wide range from -2.82 % (linear-to-convex profiles) to 67.46% (very concave profiles), with an average value of 29.01% (Table 1). From the 33 analyzed basins, 10 present concavities lower than 20%, thus indicating that they are away from equilibrium conditions.

In order to analyse how convexity is distributed over the study area we followed the approach described by Ruszkiczay-Rüdiger et al. (2009) and Matoš et al. (2014, 2016), by plotting MaxC and MaxL values in a scatter diagram (Fig. 9). This diagram shows 4 different groups; G1 and G2 groups indicate unstable young basins, group G3 includes intermediate stage basins and G4 indicates basins in a mature stage of development. Young basins of groups G1 and G2 concentrate in tributaries of the Medjerda River south of Jendouba city (basins 18 to 27), whereas in the northern area basins of groups G3 and G4 predominate (Fig. 10). The Medjerda River itself was classified as intermediate, but due to its length and complexity it cannot be analyzed together with the rest of the basins.

Figure 8. Different kinds of normalized profiles found in the study area; linear-to-convex profile (with $\text{MaxC} < 0.25$ and $\text{Cf} < 25\%$ or even negative in convex profiles, e.g. B24), very concave ($\text{MaxC} > 0.4$ and $\text{Cf} > 50\%$), e.g. B28) and intermediate profiles (with intermediate values, e.g. B1 and BMed). The location of the extracted knickpoints is drawn in green circles. The first profile shows how related parameters are calculated. Cf: percent concavity (area in orange), MaxC: maximum concavity, MaxL: distance where the maximum concavity occurs. The rest of the profiles can be found in supplementary materials (S1).

Figure 9. Scatter plot of maximum concavity (MaxC) versus source point distance (MaxL). We have differentiated 4 groups in this diagram; G1 and G2 groups indicate unstable young basins, group G3 includes intermediate basins and G4 indicates basins in a mature stage of development.

Figure 10. Drainage basins represented according to the groups obtained through the scatter plot of MaxC vs MaxL values (Figure 9) and according to the river profile morphology (convex, intermediate or concave, Figures 8 and S1).

Table 1. Values of geomorphic indexes for selected basins within the study area (see text for further explanation). ID = 0 corresponds to the Medjerda Basin.

ID	Hi	Cf (%)	MaxC	MaxL	Basin Area (km ²)	Channel Length (km)
0	0.36	39.51	0.33	0.54	23404.79	527.52
1	0.32	45.00	0.36	0.46	98.55	14.73
2	0.27	39.72	0.31	0.27	60.303	10.43
3	0.29	36.14	0.28	0.46	689.14	72.24
4	0.36	32.77	0.25	0.43	546.542	63.94
5	0.36	35.48	0.31	0.21	156.324	28.03
6	0.30	39.44	0.40	0.19	455.365	61.1
7	0.27	24.88	0.23	0.33	100.618	17.19
8	0.31	36.74	0.29	0.50	124.527	24.43

9	0.34	13.01	0.12	0.60	319.23	30.2
10	0.32	40.48	0.31	0.29	339.532	34.97
11	0.32	32.54	0.28	0.41	492.875	36.8
12	0.41	25.60	0.26	0.61	348.199	42.24
13	0.29	60.52	0.49	0.24	218.283	23.83
14	0.47	6.16	0.08	0.63	54.532	10.52
15	0.30	32.67	0.28	0.41	263.575	38.82
16	0.33	50.55	0.42	0.28	585.802	59.49
17	0.39	40.97	0.31	0.60	2573.478	168.87
18	0.48	14.65	0.14	0.34	101.873	18.84
19	0.34	24.24	0.20	0.21	342.719	35.54
20	0.35	13.80	0.13	0.42	302.171	30.12
21	0.32	27.36	0.21	0.31	55.499	13.61
22	0.26	14.99	0.11	0.70	205.079	22.08
23	0.41	8.03	0.10	0.20	231.605	33.5
24	0.45	-2.82	0.08	0.11	455.064	58.58
25	0.35	20.25	0.17	0.45	54.912	10.78
26	0.32	19.40	0.19	0.27	84.954	18.24
27	0.38	24.64	0.20	0.17	2390.379	146.31
28	0.12	67.46	0.54	0.24	167.573	29.09
29	0.27	33.87	0.25	0.45	100.416	24.37
30	0.40	-1.67	0.03	0.88	454.062	46.81
31	0.35	35.39	0.30	0.31	2219.993	167.76
32	0.21	-2.53	0.07	0.85	652.55	57.13
33	0.24	57.15	0.51	0.25	706.643	73.88

4.2 Normalized steepness index

According to the sensitivity analysis made for the study area, Chi-elevation profiles were obtained with an m/n coefficient of 0.3 for the whole drainage network. These channels were defined by using an area threshold of 1 km² to avoid including possible colluvial channels dominated by debris-flows (Stock and Dietrich, 2003; Kirby and Whipple, 2012). We used the whole drainage area of the Medjerda basin for the analysis but presented only the results within the study area. In order to spatially analyse the ksn index, we performed regressions for segments of 1 km length over chi-elevation plots and removed those with low linearity (R^2 lower than

0.95). We also removed those segments that included dams or reservoirs. With the remaining ksn segments we interpolated a surface that shows the distribution ranging from high values (red) to low values (blue) (Fig. 11). High ksn values are predominant in the western part of the studied area and coinciding with the main divide between basins draining towards Argelia and tributaries of the Medjerda River. Basins 12, 13, 16 and 17 contain the highest values delineating a NE-SW trend. This cluster of high ksn values placed in the western sector could be masking other relatively high values throughout the study area; as one with a NE-SW trend located in the centre of the study area (lower parts of basins 25, 27 and 30 and upper parts of basins 28 and 29).

Together with the spatial analysis of the ksn index, we also extracted chi-elevation plots for all the trunk channels of the 33 analysed basins (Fig. 12a). In general, the northern basins show lower slopes than the southern ones, except those within the Tellian domain (e.g. basins 12 and 13) (Fig. 12a). The Medjerda chi profile shows an interesting slope-break at its junction with tributary n° 17 near Jendouba city (Fig. 12b). At this point, the Medjerda trunk channel changes its orientation (from ENE to NNE) and increases its slope in the Chi profile, i.e. increases its ksn general trend. The tributary n° 17 maintains the same chi-elevation slope and orientation as the lower reach of the Medjerda River. This observation probably indicates that the tributary n° 17 was the old course of the Medjerda River prior to subsequent river captures occurred in the Medjerda River extending its main course towards the south (Fig. 12b).

Finally, the ksn regressed segments made on the chi profiles of the trunk channels (S2) show lower values in the northern basins, and present maximum values in transverse channels as basins 18, 24, 25, 28 and 29 and lower part of basin 30, noting recent uplifts in this southern region and thus coinciding with the ksn map (Fig. 11). These regressed ksn segments also depict

the same feature observed in the Chi profiles; ksn values for the channel n° 17 is higher west of Jendouba, but it presents similar values to the Medjerda trunk channel in its lower part.

Figure 11. Ksn values heat map for the whole study area and ksn regressed segments over the 33 selected basins. Ksn heat map has been obtained for 1 km length segments for the whole drainage network (channels with a threshold area of 1 km²). Regressed segments were selected manually by visual inspection of chi-elevation plots. The main tectonic structures are depicted. Knickpoints are displayed.

Figure 12. a) Chi-elevation plots for all the selected basins. Basins are differentiated by color and Medjerda drawn in black. Medjerda profile has a steeper gradient than its tributaries, which indicates an increase in drainage area, b) Chi-elevation profiles for Medjerda and basin n° 17, which is interpreted as the old course of the Medjerda River. Note how the lower part of the basin n° 17 maintains the same trend as mouth of the Medjerda River (old equilibrium profile).

4.3 Hypsometric curves and H_i

We extracted the hypsometric curves with their respective hypsometric integrals (H_i) for all the 33 studied basins (Table 1 and S3). H_i exhibit low values ranging from 0.12 to 0.48 with an average value of 0.33 (Table 1), characteristic of mature landscapes. Most of the hypsometric curves present concave or S-shaped profiles, as expected with landscapes in a mature stage of

development (S3). However, some curves show clear convexities in their lower parts (basins 18, 23, 24, 26, 27 and 30), which is a characteristic of increased incision of the rivers driven by headward erosion (Pérez-Peña et al., 2010; Giaconia et al., 2012a). Some basins present quite irregular hypsometric curves that cannot be classified within the previous shapes and are probably related to local active tectonics together with geological factors. We group them under the name complex curves to distinguish them from the others. We divided the hypsometric curves according to their shapes (concave, s-shaped, complex and with convex mouths) and Hi values (Fig. 13). Relatively high Hi values with convex mouths are present in transverse basins south of Jendouba city, denoting a rejuvenation processes, in agreement with previous results of normalized profiles and ksn index analysis.

Figure 13. Study basins represented according to hypsometric integral (Hi) values and hypsometric curves shapes (S3).

4.4 Knickpoint analysis

Through the analysis of ksn profiles and area-slope logarithmic plots we identified knickpoints in several rivers throughout the study area (S4 and S5). We discarded the knickpoints with ksn values lower than 2.5, as they are probably related to processes at a scale smaller than we are interested in. The knickpoints studied were classified into three categories, as explained in the methodology.

Some of those knickpoints correspond to sharp erodibility changes (Fig. 2). However, those lithological contrasts in Northern Tunisia are restricted only to small outcrops of Eocene and Jurassic carbonates and Oligocene sandstones in the Tellian domain. The lithological contrasts of these two domains could explain some moderate knickpoints in the North (basins 12 and 15) and Southwest (basin 17), and the moderate knickpoint of basin n°4 can be associated with an isolated outcrop of Eocene carbonates. The major knickpoints do not have lithological influence as they occur within Neogene sediments or Cretaceous marls in the Medjerda and basin n° 27, and over Triassic clays in basins 23 and 24 (Fig. 2). The major and moderate knickpoints that concentrate in the South of the study area agree with higher ksn segments (Fig. 11) as well as with the MaxC/MaxL groups of the normalized profiles and convex hypsometric curves (Figs. 10, 13).

Some of the knickpoints with lower ksn values fit well with tectonic structures, however, this may indicate that the activity of such structures is probably low. Other knickpoints that do not correlate either with lithology or tectonic structures could indicate some other processes, such as landslides, changes in drainage or even the aforementioned sharp lithological changes of the Eocene and Jurassic carbonates.

4.5 Fieldwork

Together with the morphometric analysis we undertook a short field campaign to study the region NW of Testour (Fig. 14). This area was selected in the light of the previous morphometric results since it includes the first major deflection of the Medjerda River together with active tectonic structures. The following section will summarise the main findings of the field campaign.

In Zarga Village we identified an abandoned fluvial channel, confirmed by substantial levels of river terraces located at the watershed between Tine and Medjerda River basins (Figs. 14, 16A), suggesting an ancient significant river flowing across the watershed through the Tine River Valley. We systematically measured dip, direction and sense of movement (when possible) of striae in pebbles produced due to pebble displacement during faulting/folding affecting the terraces. We analysed 5 field stations corresponding with abandoned terrace levels (Fig. 14). Some pebbles were measured for stations 1.4 and 2.1, 21 for 2.7, and 17 for stations 3.4 and 6.10 (Fig. 14). Striae orientations at each point on the surface pebble should be parallel to the orientation of maximum shear stress (Ruano and Galindo-Zaldívar, 2004). Following that assumption, a stress ellipsoid can be determined by fault-slip data inversion. We used the Gauss Method implemented in the software T-Tecto (Zalohar, 2009) to obtain P and T dihedral solutions. The results of the stress-inversion suggest a stress pattern with a maximum compressive stress oriented from N-S to NW-SE (Fig. 14), thus agreeing with the motion of the ETF, Zarga and Dkhila faults.

The Quaternary sediment filling of the Tine River valley located above the hanging-wall of the ETF thrust is strongly asymmetrical. We identified four terrace levels, the youngest ones being those in the center of the valley while the oldest ones occur above and in the southern side

(Fig. 15). The higher the terraces, the older and more folded they are, reaching dips up to 50° towards the NW in the oldest level (Figs. 15, 16B). Pleistocene conglomerates in these terraces show conspicuous striated pebbles that indicate a horizontal NW-SE main stress axis agreeing with the current Nubia-Eurasia convergence (Figs. 15, 16E, 16F). These observations suggest that river terraces step up the hanging-wall flat of the ETF thrust attesting for both tectonic uplift and horizontal displacement. These findings could evidence a capture of part of the Tine original basin by the Medjerda River and being the capture point close to the Zarga village, due to the continued uplift of a block likely constrained by the joint activity of the ETF, Zarga and Dkhila faults (Fig. 14). The absence of a moderate or major knickpoint associated with this capture, indicates that it should have occurred long ago, giving time to the Medjerda trunk channel to attain equilibrium conditions (Fig. 14).

Figure 14. Map with the structural data and observations surveyed in the field (red box in Figure 3). The black box shows the location of the Figure 15. Stereoplots with stress tensor results for striated pebbles. ETF for El Alia-Teboursouk fault, DF for Dkhila fault and ZF for Zarga fault.

Near the Dkhila village, we observed an unnamed 86°N fault dipping 74° towards the south that we term the Dkhila fault (DF). The Tine River presents a local knickpoint when crossing through that fault, probably accounting for its activity (Fig. 15). North of Dkhila fault, Plio-Quaternary terraces are folded and placed vertically (Figs. 15, 17A). We found that the fault movement put Trias materials above terrace sediments. The trace of this fault remains visible

until the Joumine River valley, where different segments conform a horsetail configuration. In these segments we identified 122°N striae in competent lower Eocene limestone blocks showing a dextral strike-slip movement (Figs. 15, 17B, 17C). These blocks break in 50°N reverse faults dipping 60° (Figs. 15, 17C). In one of these limestone blocks with anticlinal disposition, we observed meter to decameter open cracks with associated striae, possibly indicating coseismic deformation that suggests recent tectonic activity (Figs. 15, 17E, 17F). The orientation of cracks, parallel and perpendicular to the main fault (130°N and 45°N, respectively) with sinistral movements for the parallel ones and normal for the perpendicular ones, thus with contrary kinematics to the main faults, support this interpretation (Philip and Meghraoui, 1983; Branellec et al., 2015). Although with a probable coseismic origin, many of the cracks opening are possibly due to a landslide affecting part of the anticline's northern flank. A similar case of lateral spreading landslide has been described in the Pyrenees (e.g. Zarroca et al., 2013).

Fieldwork observations also support that the local knickpoint found in basin 32 could indicate a river capture, causing the shifting of SE draining rivers to their present position. We identified a sand point bar (Figs. 15, 17D) in a terrace located above Oligocene materials to the east of the first knickpoint of basin 32, showing paleostreams towards the SE, supporting the results obtained by the morphometric analysis.

Figure 16. Fieldwork photographs. A: Fluvial terraces in the watershed of the Tine River. B: Folded fluvial Plio-Quaternary sediments. C: El Alia-Teboursouk fault zone (ETF). D: Sub-vertical Plio-Quaternary deposits on the footwall of the ETF fault. E and F: Striated pebbles in a terrace of the Tine River valley.

Figure 17. Fieldwork photographs. A: Folded and sub-vertical Plio-Quaternary terraces (some strata are marked in black). B: Dextral strias in Eocene limestones. C: Dextral strike-slip fault near a reverse fault. D: Sand point bar indicating paleocurrents towards the SE. The symbol indicates paleocurrents towards the terrace. E: Probable coseismic cracks. The red box highlights striae in a N130E fracture. F: Two different families of probable coseismic, N130E and N45E.

5 Discussion

5.1. Drainage network anomalies associated with active faulting

Most of the ksn anomalies observed in northern Tunisia occur parallel and delineating the uplifted blocks of faults developed in the context of NW-SE convergence between Nubia and Eurasia (Fig. 11). These faults are either reverse-sinistral faults like the El Alia-Teboursouk fault and their associated folds, or other dextral and normal faults, which we will discuss below. Furthermore, these anomalies delineate in some cases faults that have not been mapped previously, but that we have mapped thanks to the morphotectonic analysis and later identified in the field (Fig. 18). This is the case of the WNW-ESE Dkhila dextral-reverse fault. This fault reaches a length of approximately 30 km and shows evidence of recent activity, having cut Pleistocene terraces and the Tine River valley (Fig. 18).

The main reverse-sinistral faults that show a morphotectonic signal in northern Tunisia after analysing different indices are the El Alia Teboursouk and the Cap Serrat – Gardimaou faults, two of the most important sinistral faults in the region (Fig. 18). Although not as evident as the ETF and CSGF faults, the RKTF and TEF faults also show high ksn values supporting recent tectonic activity (Fig. 11). The hypsometric curves also support uplift in some areas, interpreted as related to the movement of sinistral-reverse faults, as for the lower parts of basins 23 and 24. Nevertheless, these convexities near the source could point to an active incision wave from the Medjerda main course upstream, which, in turn, may reflect the Medjerda incision retreating from a far field area due to a base-level change at the Medjerda mouth.

Dextral faults are interpreted as conjugate to sinistral faults, or as transfer faults of reverse faults. These faults have WNW-ESE trends that match with the regional tectonic compressional vector. Few dextral faults are described in the literature, and we could identify

some new ones in the field, like the Dkhila and Zarga faults (Fig. 14). These faults cut Pleistocene sediments (Fig. 15) and, together with the ETF, form an uplifted block that could have isolated the upper part of the Tine River and favored its capture by the Medjerda main channel. The activity of E-W dextral faults could also have contributed to isolate this block (Fig. 14).

Figure 18. Northern Tunisia active tectonics map derived from this work. In red are shown the active faults with their IDs. In purple are shown the active faults described in this work for the first time (Dkhila and Zarga faults). In blue are shown the main rivers. Focal mechanism solutions extracted of the compilation of Soumaya et al. (2015). The focal mechanism solutions are plotted in the barycenter of the epicentral and weighted by magnitudes. The color of focal mechanisms type is based on the Frohlich triangle diagram (above left). NF: normal faulting, TF: thrust faulting, SS: strike-slip faulting, TS: thrust to strike-slip faulting, and NS: normal to strike-slip faulting.

The normal faults in northern Tunisia have a NW-SE disposition and develop small tilted basins hosting alluvial fans (Belguith et al., 2011). Moderate k_{sn} values on the footwall areas of

these faults suggest their activity. This is clear in the southeastern sectors of the studied region (upper parts of basins 31 and 27) or in the Mateur's fault zone (Fig. 18). The movements of many of the faults described above are causing landscape readjustments that induce river captures as described below. Some of these faults have associated minor or local knickpoints (Figs. 11, S4, S5). The low ksn values related to these knickpoints may indicate that the activity of these structures is low. This observation fits well with the overall topography in northern Tunisia, with gentle slopes and no deeply incised canyons.

Moderate knickpoints are found associated with the competent rocks of the Tellian domain (basins 12, 15 and 17) or with isolated outcrops of competent rocks (Eocene carbonates in basin n° 4, Fig. 11). Moderate knickpoints associated with the competent rocks of the Tellian domain agree with the positive anomaly in ksn values parallel to the thrust contact between the Tellian and the Atlas domains (Fig. 11). This contact places less erodible sandstones above mostly pelitic rocks of the Atlas domain. The local knickpoint in the Medjerda east to Zarga, despite not lying directly over the Dkhila fault itself, could be related to the uplift generated by the block formed by the ETF, Zarga and Dkhila faults.

Moderate and major knickpoints are found in the upper reach of the Medjerda River some kilometers upstream Jendouba, in transverse channels 18, 19, 20, 23, 24, 25 and 26 (Fig. 11). They agree with higher ksn segments (automatic and regressed segments, Fig. 11), MaxC/MaxL groups of the normalized profiles and convex hypsometric curves (Figs. 10, 13) and could be related to a more general drainage reorganization taking place in northern Tunisia.

Finally, some knickpoints are also located over the contact with Triassic evaporites (basin 24, west of Kef village (Fig. 2)). The high lithological contrast, together with the possibility of halokinesis could also play a role by "accelerating" knickpoint formation and upstream

migration. In these areas, additional field mapping and a finer structural analysis could shed light on the matter.

5.2. General drainage reorganization related to regional tectonics

River captures are the main fluvial mechanism in northern Tunisia driving a general fluvial network reorganization. We have identified several fluvial captures throughout the studied area. These captures are evidenced by different features like abandoned fluvial channels and terraces, knickpoints and morphometric results. The overall capturing process is well depicted in the Chi profiles for the main channels, those profiles show how the Medjerda main channel is gaining area as its slope is higher in its upper parts compared to the lower parts (Fig. 12A). A nice example of these captures can be viewed in the Tine River near Zarga village. The joint activity of the ETF, Zarga and Dkhila faults produced and uplifted a block that isolated the upper reach of the Tine River, boosting its capture by the Medjerda main channel.

There are basically two general river orientations in the drainage network of NE Tunisia; axial rivers striking NE-SW parallel to the compressional structures, and transverse channels striking NW-SE to NNW-SSE. The transverse channels of the eastern side of the Medjerda River present higher ksn trends, convex hypsometric curves and higher values of MaxC/MaxL (Figs. 10, 11, 13), thus suggesting that the capture process is driven by the replacement of the axial drainage by a transverse one. This observation agrees with the expected behavior in the normal evolution of a drainage network in a mature relief developed under a NW-SE compressional setting, where higher structural relief and steeper regional slopes prompt the development of a transverse drainage system (Babault et al., 2012). However, the Medjerda River remains as the “main attractor” for the whole drainage system, despite maintaining a general trend parallel to

the main structural relief, what can be considered an anomalous flow contrary to the natural transverse drainage development of mature orogens.

The major trends of the relief of Tunisia and eastern Algeria can be viewed in the filtered topography (Fig. 19). Although tectonic transport related to thrusting in Tunisia has been mostly towards the southeast, the filtered topography map shows a regional long-wave topographic high that coincides with the southwest Atlasic front, along the boundary between the Sahara and Tunisian Atlas. This region is also characterized by the highest seismicity with strike-slip focal mechanisms (Fig. 19) and by the presence of active dextral NW-SE oriented faults, like the Gafsa fault (Ben Hassen et al., 2014). The highest altitudes in this region impose a general topographic gradient towards the northeast favoring the development of large axial catchments, like the Medjerda River. The Medjerda River valley drains towards a general depression in the filtered topography. Onshore, palustrine environments and lakes with outlets towards the Sicily channel and the Gulf of Gabes characterize the coastal areas of this topographically depressed region. Considering the rather uniform crustal thickness of Tunisia in a NE-SW direction (Research Group for Lithospheric Structure in Tunisia, 1992) it is possible that this topographic low region could be related to some dynamic topography effect. Actually, this topographically depressed area lies above the region where the slab body imaged in the Tunisian mantle would link with the African lithospheric mantle (Wortel and Spakman, 2000; Piromallo and Morelli, 2003; Fitchner and Villaseñor, 2015). Although the slab images in this region are badly resolved because of lack of seismic coverage in Tunisia, independent seismic refraction data show the presence of a high-velocity reflector at 87 km under this region (Research Group for Lithospheric Structure in Tunisia, 1992), which together with intermediate depth seismicity in the Sicily Channel (Chiarabba and Palano, 2017) supports the existence of a Tunisian slab

connected with the African mantle lithosphere (Booth-Rea et al., 2018; Fig. 20). This slab probably links with the African lithosphere under the southernmost segment of the South Atlasic fault and under the North-South Axis, producing dynamic topography in the form of a depression from the Gulf of Gabes towards the Sicily channel (Booth-Rea et al., 2018; Fig. 20). Thus, dynamic topography related to slab pull, together with tectonic activity along the south Atlasic mountain front, are important factors determining the apparently anomalous longitudinal orientation of the Medjerda River. Uplift along the south Atlasic dextral transfer zone might also be related to upper-mantle flow through a Tunisian Atlas slab window between the Sahara and Tunisian Atlas (Figs, 19, 20). This boundary must have worked as a dextral STEP boundary since the Middle Miocene, namely the Tunisian Atlas Transfer Fault (TATF in Fig. 19).

Even though the location of the deformation fronts may be driven by a narrow segment of the underlying slab, the broadening of the deformation region from east Algeria to Tunisia (Fig. 19) may be related to the Africa-Western Mediterranean crustal and lithospheric structure. In most of Algeria the location of recorded seismicity is narrow and roughly maps the transition from the thick African lithosphere to the thinner Algerian basin Miocene oceanic-type lithosphere. Northern Sicily is similar to Algeria in that it has a well-defined seismicity band that occurs near the boundary between the continental and proto-oceanic crust of the Tyrrhenian. Thus, we propose that crustal deformation is influenced by lithospheric thickness, localizing deformation in the transition from comparatively thicker to thinner. In contrast, the southern displacement of the plate boundary in Tunisia might be related to the fact that the northern Africa lithosphere converging NW is encountering the continental lithosphere of Sardinia-Corsica and not a thin oceanic plate. This configuration would promote the formation of a broader more diffuse deformation zone in Tunisia compared to the neighboring regions.

Figure 19. Spatial distribution of focal mechanism solutions and horizontal velocities (with 95% error ellipses) given with respect to the Eurasian plate (modified from Serpelloni et al., 2007)) along the Nubia Eurasia boundary in western Mediterranean. The focal mechanism solutions have been taken from the Global CMT Catalog for the 1976-1996 period and from the European-Mediterranean RCMT Catalog for the 1997-2015 period. The focal mechanisms are plotted in the barycentre of the epicentral and weighted by the earthquake magnitudes. The background shows a filtered topography (25 km radius mean filter) that highlights the regional topographic trends. AS: Algerian Slab, TS: Tunisian Slab.

Figure 20. Schematic model of the tectonic setting and its influence on topography and drainage in northern Tunisia (modified from Booth-Rea et al., 2018). Filtered topography shows the general topographic gradients in the region and their possible relation to the interplay between plate convergence and deep mantle mechanisms. The Tunisian slab has been drawn, based on the model proposed by Booth-Rea et al. (2018). Slab pull would drive negative buoyancy in the Sicily channel and the Gulf of Gabes, while positive uplift would occur above delaminated regions of Northern Tunisia in the headwaters of the Medjerda River, or related to transpressive tectonics along the Tunisian Atlas STEP boundary. Continental-mantle slab tearing along this STEP boundary developed the Tunisian Atlas Slab window (TAS).

6 Conclusions

Our morphotectonic analysis sheds light on the different mechanisms that govern the development of the drainage of northern Tunisia. At the scale of the whole Tunisian Atlas the main mechanisms that have influenced the drainage evolution are NW-SE shortening related to the Nubia-Eurasia plates convergence, to slab pull under eastern Tunisia, and as a result, the

uplift of western Tunisia along the south Atlasic deformation front that operates as a dextral-reverse transfer zone.

NW-SE horizontal shortening has given rise to NE-SW oriented thrusts and sinistral-reverse faults that condition the development of large axial valleys along their footwalls and associated synclines. Uplift along the largest structures has favored the development of short NW-SE transverse catchments along the southeastern deformation front of the Tunisian Atlas, with rivers draining to the Pelagian foredeep basin. However, the main drainage in northern Tunisia is the axial Medjerda valley that runs from SW to NE above the Tunisia Atlas wedge-top basin and drains into the Gulf of Tunis.

The catchment area of the Medjerda River has grown through time by capturing other longitudinal valleys to the south and east of its initial drainage divide. These series of captures formed transverse tributaries to the Medjerda River that show the highest convexity and hypsometric integral values. In some cases, these captures could have been driven by an increase in incision rate of the Medjerda tributaries, related to uplift associated with active tectonic structures like the Alia-Teboursouk reverse fault.

Lithologic contrasts between the Tellian sandstone units and more erodible North Maghrebian paleomargin-derived rocks also seem to influence the drainage in northern Tunisia. The contact between these domains is marked by a clear ksn anomaly and coincides with the main divide between basins draining to the Argelian basin and the northern tributaries of the Medjerda River.

The morphometric analysis carried out in this work support that active faults have a sparse distribution throughout the studied area. This distribution agrees with the sparse and scarce seismicity of the area and contrasts with adjacent parts of the Nubia-Eurasia boundary in

northern Algeria and northern Sicily. We propose that the main reason of the different seismicity rates in Tunisia is due to its extended continental platform and its lack of oceanic lithosphere northward. In Tunisia, the deformation is partitioned across a comparatively larger number of structures whereas in northern Algeria and Sicily deformation is comparatively focused at the rheological change between the continental and oceanic plates.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights

1. Morphometric relief analysis for the tectonic characterisation of northern Tunisia
2. Recent fluvial captures are the main factor driving fluvial network reorganization
3. River captures are caused by crustal shortening structures and mantle dynamics
4. The Medjerda River has increased its drainage area during the Quaternary
5. The morphometric analysis supports a sparse distribution of active faulting