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Active tectonics and GPS data analysis of the Maghrebian thrust belt and Africa-Eurasia plate convergence in Tunisia

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ABSTRACT

The Atlas Mountains of Tunisia belong to the seismically active zone of the Africa (Nubia) - Eurasia plate boundary in the central-western Mediterranean. We study the eastern section of the Maghrebian thrust belt using a subset (6 days) from each of 5 years (2014 to 2018) of permanent (survey-mode) GPS data and active tectonics. WNW to NNW-trending velocities express crustal motion and geodetic strain fields from the Sahara Platform to the Tell Atlas, consistent with African plate convergence. To the south, the velocities and trajectories indicate nearly WNW-ESE-trending right-lateral motion of the Sahara fault-related Atlas fold belt with respect to the Sahara Platform. Farther north and northeast, the significant decrease in velocities between the Eastern Platform (Sahel), Central Atlas and Tell Atlas and the clockwise rotation mark the NNW-trending shortening deformation associated with local ENE-WSW extension visible in the Quaternary grabens. The velocity field and strain distribution associated with the active E-W- to WNW-ESE-trending right-lateral faulting and NE-SW fault-related folds illustrate the transpression tectonics and support the identification of four tectonic domains north of the Africa-Nubia Platform in Tunisia. The transpression reduces northward when reaching the Central and Tell Atlas. These results change our perception of the Africa-Eurasia plate boundary previously located along the western Mediterranean coastline.

1. Introduction

The Eurasia-Nubia (Eu-Nu) plate boundary in the western Mediterranean includes the fold-and-thrust belts of the Atlas Mountains. These mountains belong to the eastern end of the Maghrebian thrust belt and result from transpression tectonics along the NNW-SSE to N-S oblique convergence of Africa towards Eurasia (Frizon de Lamotte et al., 2000; Faccenna et al., 2004; Meghraoui and Pondrelli, 2012; Jolivet et al., 2016). The 4 to 6 mm/yr Eu-Nu convergent motion governs this seismically active zone situated between the Algerian Atlas Mountains to the west and Sicily to the east (Nocquet and Calais, 2004; D'Agostino and Selvaggi, 2004). The oblique convergence is expressed by E-W- to WNW-ESE-trending right-lateral strike-slip faults associated with E-W- to NE-SW-trending thrust faults that affect the Neogene and Quaternary units of the Tell and Sahara Atlas of Tunisia (Fig. 1; Ben Ayed and Zargouni, 1990; Bouaziz et al., 2002; El Ghali et al., 2003; Gharbi et al., 2014). However, the active deformation of continental Tunisia is poorly known due to the lack of geodetic results and analysis of present-day active tectonics. Indeed, compared with previous GPS results in the neighboring Tell Atlas of Algeria (Bougrine et al., 2019) and in southern Italy (Serpelloni et al., 2007; D'Agostino and Selvaggi, 2004), continental Tunisia remains a significant gap that affects our understanding of Mediterranean geodynamics.

In this paper, we present the active deformation of the Maghrebian thrust belt using GPS results from the survey mode record of 21 stations well distributed across Tunisia between 2014 and 2018. Horizontal GNSS time series and velocities are presented along with the deformation field. The data analysis reveals a subdivision in complex tectonic domains and related crustal motion with regard to the Eurasia reference system. The active tectonics and related strain fields in Tunisia are discussed within the framework of the seismotectonics of the western and central Mediterranean regions.

2. Neotectonic and seismotectonic setting

Continental Tunisia shows various geological structures and tectonic domains mainly limited by N-S and E-W-trending strike-slip, NE-

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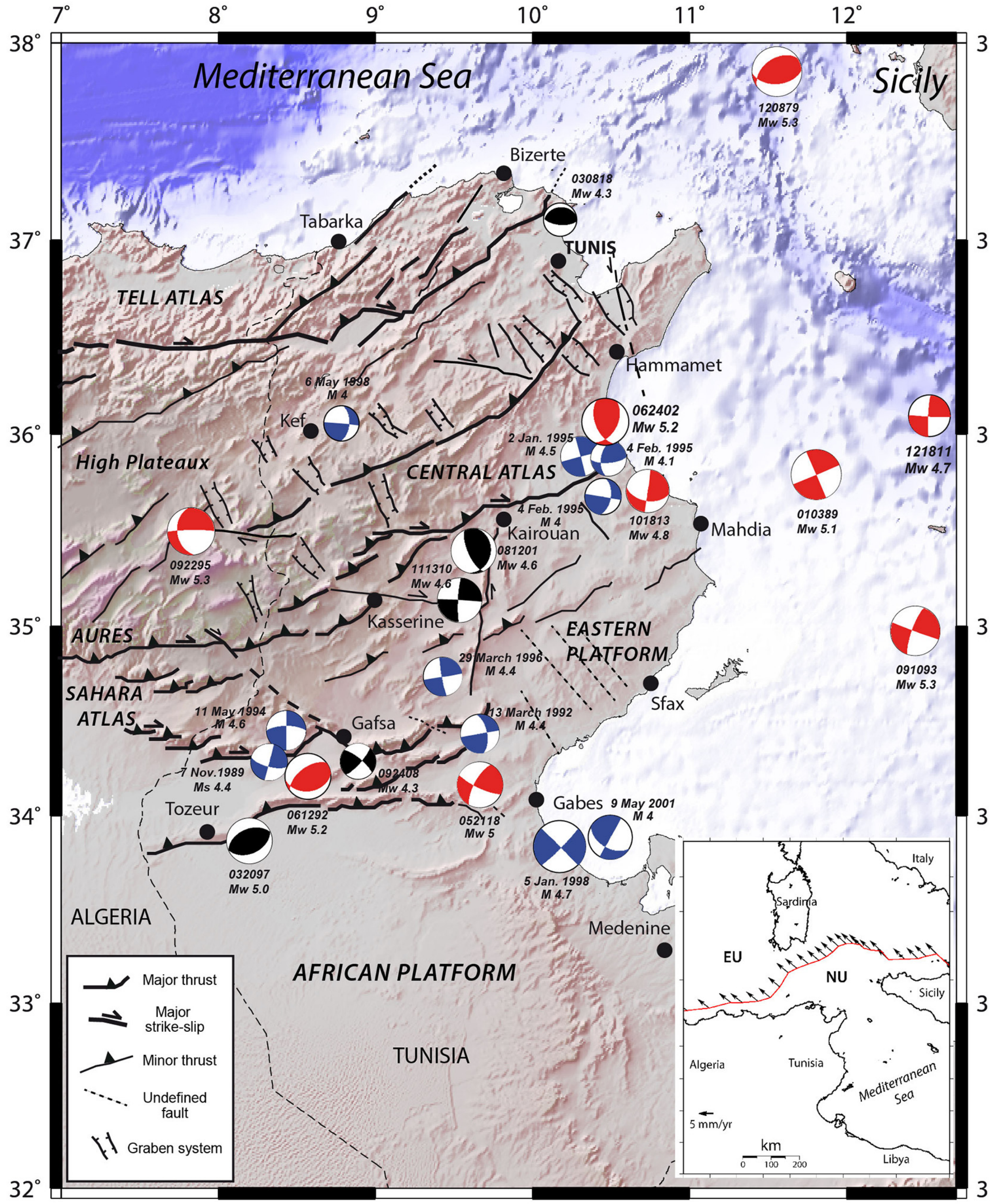

Fig. 1. Seismotectonic map of Tunisia. Neotectonic faulting is from Bahrouni et al. (2014), and focal mechanism solutions for the largest instrumental earthquakes are from CMT-Harvard database (2019) (red), RCMT-INGV (n.d.) (black) and Institut National Meteorologie of Tunis (blue). Topography and bathymetry are from GEBCO1 grid data (Smith and Sandwell, 1997).
Inset: Eu-Nu Plate boundary (Bird, 2003) and inferred convergence vectors based on the Euler pole provided by Altamimi et al. (2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

SW-trending thrust and NW-SE-striking normal faults with graben structures (Fig. 1; Frizon de Lamotte et al., 2000; Bouaziz et al., 2002; El Ghali et al., 2003; Bahrouni et al., 2014). The geological and tectonic background of Tunisia includes the northern Tell Atlas, which is a narrow E-W-trending strip (~50 km) of nappe tectonics with overthrust faults and diapir structures. The Central Atlas, which occupies a major part of continental Tunisia and can be correlated with the High Plateaus of Algeria, is characterized by NE-SW-striking thrust faults and NNW-SSE-trending Neogene and Quaternary grabens. To the southeast, a passive continental margin includes the Sahel (Eastern Platform in Fig. 1) geological domain composed of large synclines and anticlines buried beneath Neogene and Quaternary deposits. Farther south, the Sahara Atlas and related E-W-trending en echelon Neogene and Quaternary folds constitute the boundary with the African Platform. These four geological domains form the Maghrebide tectonic belt with predominant thrusting and folding in Tunisia. Local and regional tectonic studies on the stress distribution determined from fault plane kinematics and earthquake focal mechanisms indicate the persistence of the N-S to NNE-SSW shortening direction during the Plio-Quaternary period across the Maghrebian thrust belt of Tunisia (Rebaï et al., 1992; Chihi, 1992; Ghribi and Bouaziz, 2010; Bahrouni et al., 2014).

Seismotectonic studies correlate Plio-Quaternary faults with shallow seismicity and indicate the main characteristics of the active deformation across the northern Tell, Central Atlas and Eastern Platform (also

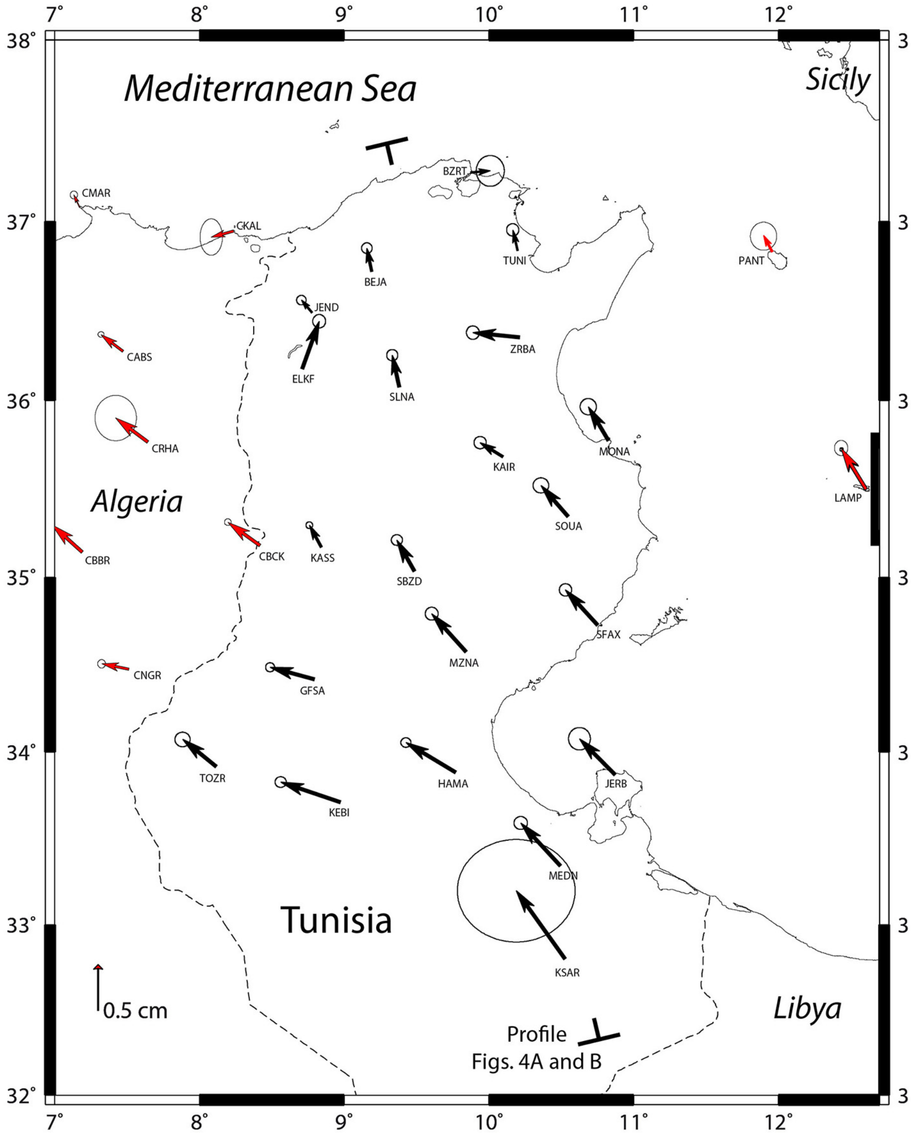

Fig. 2. GPS trends and velocities (black arrows) across continental Tunisia. Error ellipses (95% confidence) are scaled by the ratio of the formal error and repeatability as estimated by the Kalman filter step. Red arrows are the results from Bougrine et al. (2019) for Algeria GPS stations and from D'Agostino and Selvaggi (2004) for Lampedusa and Pantelleria GPS stations. Profiles of GPS velocities are shown in Figs. 4A and B. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

called the Sahel tectonic domain) of Tunisia (Hfaiedh et al., 1985; Philip et al., 1986; Ben Ayed and Zargouni, 1990; Saïd et al., 2011; Soumaya et al., 2018). The N-S-trending and left-lateral major tectonic lineament that forms the western limit of the Eastern Platform and its ~ 4-km-thick Neogene and Quaternary deposits is affected by active E-W right-lateral strike-slip faulting. Although the recent seismicity catalog does not reach Mw 5.5 (Table S1), historical documents report the occurrence of large earthquakes (Guidoboni et al., 1994; Ambraseys, 2009; Kharrat et al., 2018; Bahrouni et al., 2020) that attest to significant crustal deformation (Fig. 1). Fault kinematics from recent focal mechanism solutions are consistent with E-W-trending right-lateral faults, and NE-SW faulting and folding of Quaternary formations are visible throughout the Maghrebian thrust belt of Tunisia (Chihi, 1992; Mejri et al., 2010; Saïd et al., 2011; Bahrouni et al., 2014). NW-SE-striking faults with right-lateral slip, such as the Gafsa fault in the southern Atlas, may act as thrust-related tear faults between the E-W- to NE-SW-trending fold-related faults and may generate earthquakes with Mw $>$ 4 (e.g., on 24 Sept. 2008, Table S1; Athmouni et al., 2019). The active NNW-SSE-trending grabens in the South and Central Atlas of Tunisia and partly in Algeria attest to the E-W to NE-SW extension (Philip et al., 1986; Ben Chelbi et al., 2013). However, focal mechanism solutions of earthquakes display strike-slip and thrust faulting with NW-SE-trending P axes. The study of instrumental seismicity, such as the 1989 Metlaoui earthquake (Ms 4.4, Dlala and Hfaiedh, 1993) and the 1995 Sahraoui earthquake (Mw 5.3, Institut National de la Météorologie, 1996), and the focal mechanisms (Table S1) shows the predominance of thrust and strike-slip faulting that characterizes the transpressive character of crustal deformation in the Tunisian Atlas Mountains.

3. GPS data analysis

The GNSS network consists of 21 sites equally distributed from north to south across Tunisia, with the exception of the southernmost uninhabited part in the desert (Fig. 2). The GNSS stations are permanent stations consisting of concrete pillars on bedrock and established by the “Office de la Topographie et du Cadastre” de Tunisie (OTC). However, they were used in survey mode because only 6 days of data

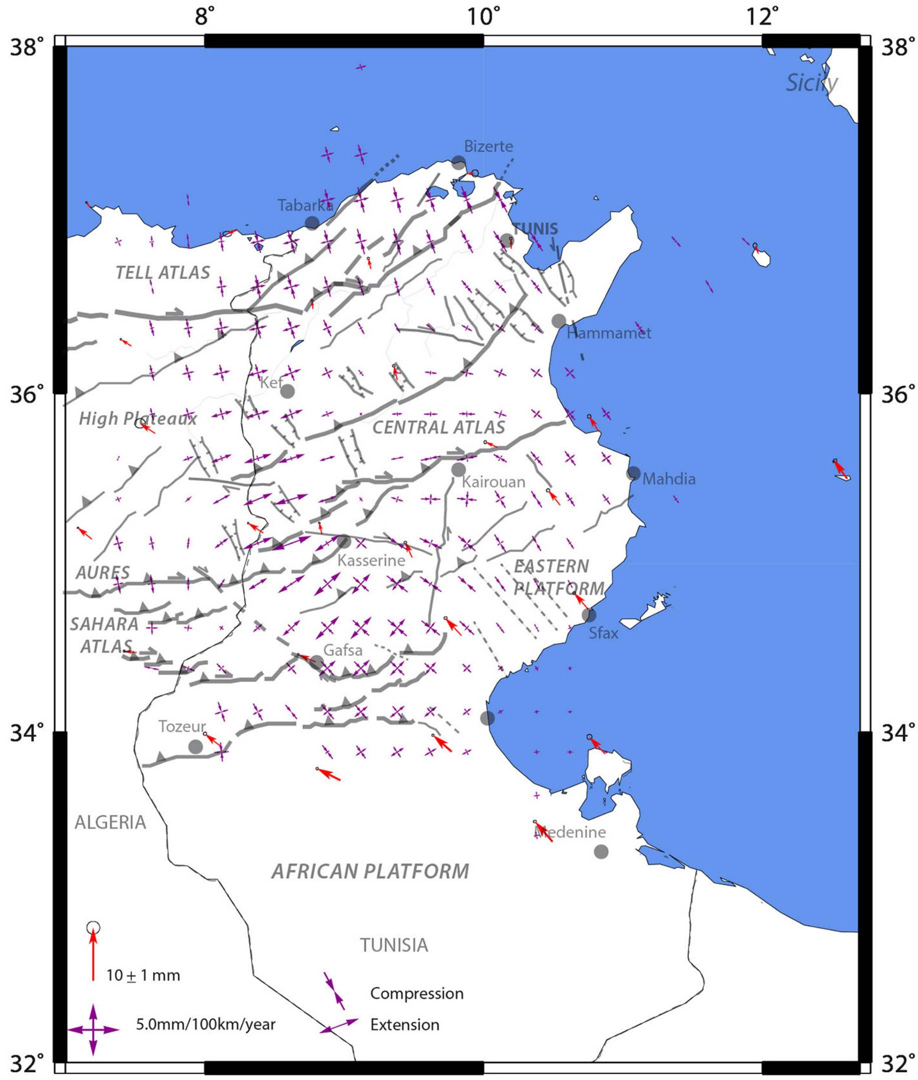

Fig. 3. Strain distribution and rate across continental Tunisia. The background tectonic features are from Fig. 1, and the red arrow is the GPS velocity. Only the grid nodes with the diagonal term of the resolution matrix > 0.1 are plotted. The GPS results of stations KSAR, ELKF and ZRBA are not taken into account for the strain calculations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

per year were made available between 2014 and 2018, and always at the same period of the year. This is equivalent to 5 measurement campaigns of 6 days with the great advantages of having no error in repositioning the antennas and no change in GNSS equipment. All stations record a complete dataset between 2014 and 2018 except for stations KSAR and BZRT, which are measured only from 2017 to 2018 and from 2016 to 2018, respectively. The processing is carried out using the GAMIT/GLOBK 10.6 software (Herring et al., 2015) in a completely standard way with the commonly used processing parameters. First, we estimate loosely constrained daily solutions using GAMIT for all the Tunisian GPS survey-mode data and a subset of 20 selected IGS stations and then apply a Kalman filter to estimate a set of coordinates and velocities for each site. Second, we apply a cleaning process by detecting and removing outliers. The time series are shown in Figs. S1 and S2, and the velocity field is shown in Table S2. Finally, a second round of estimating station coordinates and velocity using clean solution is applied to all sites referenced to the ITRF2014 framework (Altamimi et al., 2016).

The velocities in the Eurasia fixed reference frame (Fig. 2) are obtained using the Euler poles of Eurasia determined by Altamimi et al. (2017). To estimate a realistic margin of standard deviations, we apply the MIDAS tool (Blewitt et al., 2016) for all permanent GNSS sites and scale the standard deviations by the ratio of the formal error and repeatability estimated by the Kalman filter step (Hollenstein et al., 2003; Saleh and Becker, 2015; Alothman et al., 2016). The uncertainties with a 95% confidence level are fairly low except for KSAR and BZRT, probably due to the limited times of observation (~2 years and ~3 years, respectively; Fig. 2). Using the GPS velocities and the strain tensor inversion baseline (STIB) method proposed by Masson et al. (2014), we calculate the strain distribution and rate based on a 100 km correlation length and a standard error of 0.5 mm/yr (Fig. 3). The average distance between GNSS stations and the dimensions of the main active tectonic structures allow us to use a 100 km distance for strain calculations. We also project north and east velocities along a N-S profile and note that the KSAR, ZRBA and ELKF stations appear as outliers (in red in Figs. 4A and B) because their velocities and error ranges are too different from their neighbors to be integrated into any tectonic interpretation. These three stations are not taken into account for the strain calculations.

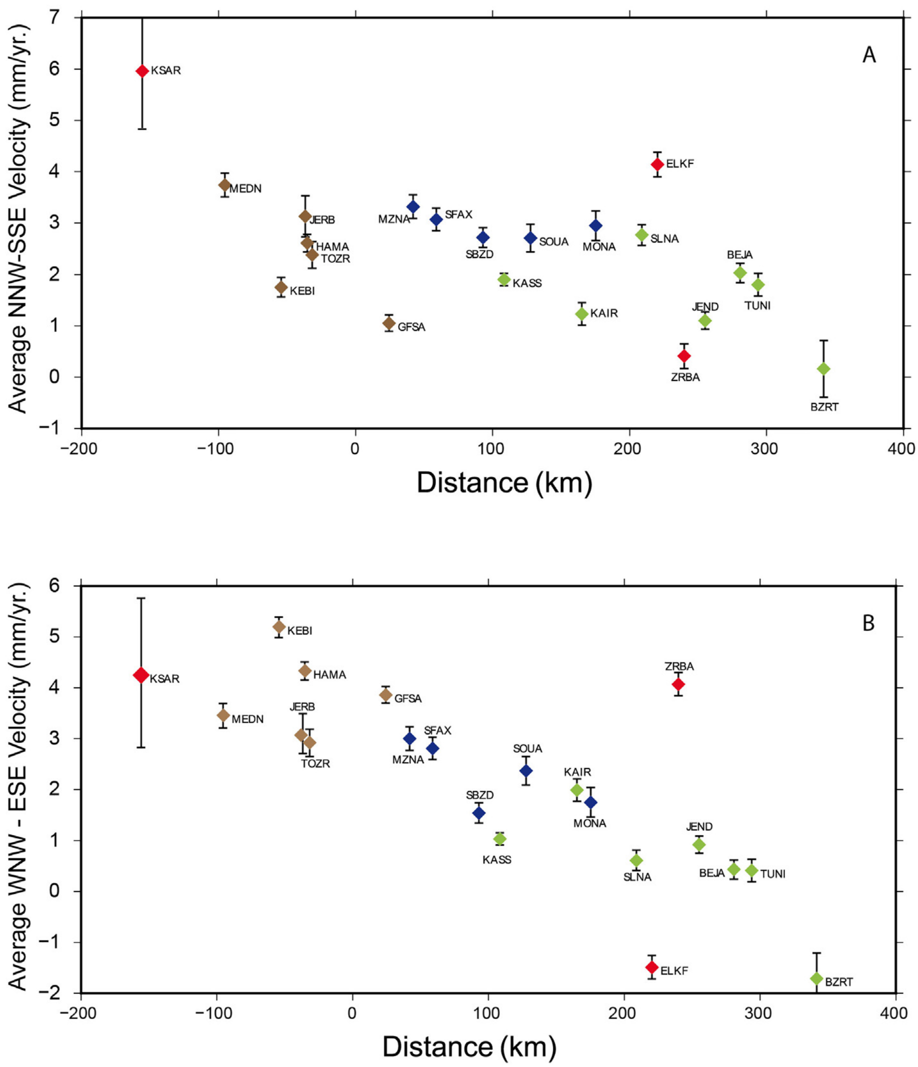

Fig. 4. Resolved parallel and perpendicular GPS velocity components on profile across the Atlas Mountain belts of Tunisia (See Fig. 2 for profile location). (A) GPS velocities projected along the NNW-SSE and (B) GPS velocities projected parallel to WNW-ESE. Colors indicate the different geological domains of Tunisia as shown in Fig. 5 (brown for the Sahara Atlas and African Platform, blue for the Eastern Platform and green for the Central and Tell Atlas). The results for GPS stations KSAR, ELKF and ZRBA in red are considered outliers. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Active deformation and strain rates

The deformation field indicates the distribution of crustal deformation with clear strain partitioning and the existence of different tectonic domains (a domain is a region with comparable tectonic structures) across continental Tunisia (Fig. 3). In the South-Sahara Atlas and the African Platform, stations MEDN, JERB, HAMA and KEBI move at approximately 5–7 mm/yr in a WNW direction and show a 2 to 3 mm/yr velocity difference with right-lateral strike-slip motion when compared with stations TOZR and GFSA located farther north and northwest. Taking into account the E-W-trending thrust-related folding between KEBI, TOZR and GFSA and comparing the northing components between stations, we obtain a 0.23 ± 0.04 mm/yr shortening rate that agrees with the 0.21–0.34 mm/yr reverse component of the slip rate over the past 50 kyr derived from tectonic geomorphology and paleoseismic investigations across the Gafsa fault (Saïd et al., 2011). The Eastern Platform and Central Atlas region includes GPS sites that have an average NNW- to NW-oriented velocity, with an overall ~45° anticlockwise vector rotation with respect to GPS sites on the African Platform (Fig. 5). The ~45° anticlockwise rotation and 2 to 3 mm/yr difference between WNW- and NNW-trending velocities imply a right-lateral motion along the E-W-striking thrust-related folds, consistent with the neotectonic observations of Saïd et al. (2011) and Bahrouni et al. (2014). With the left-lateral N-S-trending fault zone that limits the Eastern Platform, which is affected by active folding and E-W right-lateral faulting and folding, the platform may not be considered a rigid block. Both right-lateral strike-slip movement and slight compression are observed in the strain rate tensor (Fig. 3). A notable strain distribution is the ENE-WSW-trending extensional field west of the Central Atlas and across the boundary with Algeria that coincides with the NNW-SSE-trending Quaternary grabens (Figs. 1, 3 and 5). An estimated ~3 mm/yr extension rate across the Central Atlas inferred between station SLNA and nearby Algerian GPS stations is comparable with the 6–7 mm/yr Neogene opening rate across the Sicily Channel (Belguith et al., 2013). As the error estimate on the strain rate tensor is relatively difficult, we use the resolution proxies proposed by Masson et al. (2014) to determine the quality of the results. Outlier data from stations KSAR, ZRBA and ELKF are not used for strain rate tensor calculations.

Figs. 4A and B show gradually decreasing GPS velocities from the African Platform towards the NW to the Central Atlas and from the Eastern Platform to the north, crossing the Tell and Central Atlas. A comparable change, although with a smaller difference, is observed between the WNW-trending ~7 mm/yr for stations HAMA and KEBI and ~5 mm/yr for stations GFSA and TOZR in southeast Tunisia. Farther east and northeast in the Eastern Platform and Central Atlas, the trend and magnitude of velocities mark the shortening movements associated with NE-SW thrust-related folding. The active tectonics and velocity field lead to the identification of four main tectonic domains: the Tell Atlas, the Eastern Platform, the Central Atlas and the South-Sahara Atlas north of the African Platform (Figs. 2 and 5). The transpressive tectonics with slip partitioning between strike-slip and shortening movements that affect the eastern Maghrebian thrust belt are

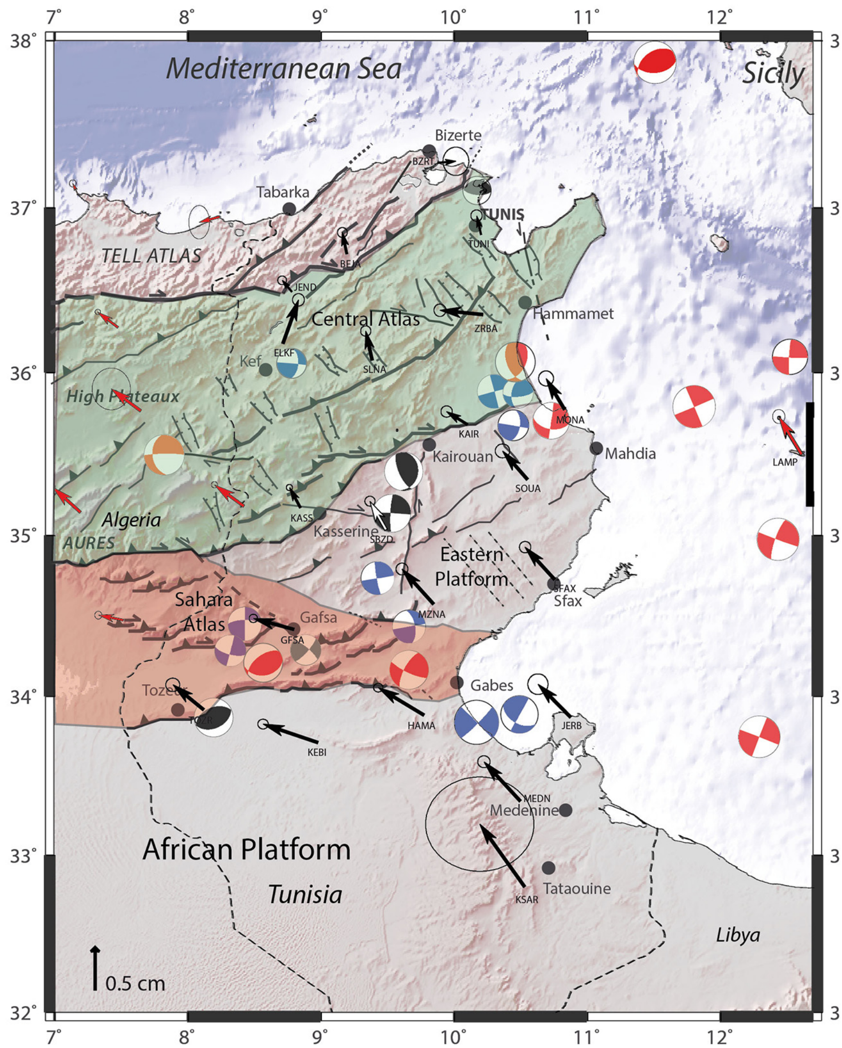

Fig. 5. Tectonic domains (background color) with fault kinematics (see also Fig. 1) and active deformation as shown by GPS velocities (arrows; Fig. 2). The NNW-SSE decrease in velocities across Tunisia is also shown in the diagram of Fig. 4A, where we observe a significant shortening along quasi-NNW-trending velocities for stations KSAR, MEDN, MZNA, NKLG, SLNA and BEJA. Right-lateral deformation is well observed between the African Platform and South Atlas - Eastern Platform region (Figs. 3 and 4B). The change in vector directions becomes more obvious for northern stations SLNA, BEJA, TUNI, and ALKF and significant for both velocity and trend at stations JEND, BEJA and BZRT. The correlation of active tectonic structures with GPS velocities implies the tectonic domain subdivision consisting of the Sahara Atlas, Eastern Platform, Central Atlas and Tell Atlas.

comparable with active tectonic structures in Algeria (Meghraoui and Pondrelli, 2012). The strain rate and seismotectonics across the main tectonic domains may also explain the more frequent and destructive earthquakes in the Central and Sahara Atlas (Ben Ayed and Zargouni, 1990; Gueddiche et al., 1992; Dlala and Hfaiedh, 1993).

5. Discussion and conclusions

The active tectonics and GPS results in Tunisia provide new insights into the geodynamics of the Eu-Nu plate boundary in western Mediterranean regions. GPS results indicate that the crustal motion (reaching ~7 mm/yr NW-trending velocity) of the African Platform compared to the 5–2 mm/yr convergence rate of the Maghrebian thrust belt is critical and attests to the amount of tectonic transpression at the plate boundary. The decrease in GPS velocities towards the N and NW in Tunisia with ~45° anticlockwise rotation across the geological domains outlines the significant crustal deformation in tectonic domains with slip partitioning across the Maghrebian thrust belt in North Africa. The active tectonics of Tunisia with GPS results correlated with the background geological formations allow the identification of four main tectonic domains north of the African Platform (Fig. 5).

5.1. Tectonic structures and strain rate field

The fold-and-thrust belt in Tunisia is a complex geological domain where cumulative Mesozoic-Cenozoic structures are predominant and may conceal Quaternary tectonics (Bouaziz et al., 2002). North of the African Platform, the identification of active faulting and related seismicity can be distinguished from the pre-Neogene and Neogene tectonic features (Bahrouni et al., 2014). GPS velocities and seismotectonic features provide the basis for the identification of the four main tectonic domains in Tunisia (Fig. 5). Most of the large earthquakes in the last century occurred predominantly across the south-central and Sahara Atlas regions, where GPS strain rates are significant (Table S1 and Fig. 1). In the profile with GPS velocities in Fig. 4A, we observe that the N-S-trending shortening starts north of stations MEDN - JERB and decreases by 3 to 4 mm/yr farther north, mainly across the Central and Tell Atlas. Indeed, except for the Central Atlas, the shortening strain distribution is predominant in the Sahara Atlas and Eastern Platform to the south and across the northern Central Atlas and Tell Atlas (Figs. 3 and 5). GPS velocities that generally decrease from south to north in Fig. 4A indicate significant shortening deformation with an estimated ~20 nstrain/yr across the eastern section of the Maghrebian thrust belt (Fig. 3).

The WNW to NW trend and velocities across the Sahara Atlas in Tunisia and the Aures Mountains in Algeria show remarkable consistency with slip portioning between E-W right-lateral faulting and NNW-SSE folding (Figs. 1 and 5). Indeed, a major contribution of GPS results here is to show that a significant amount of transpressive deformation reaches ~3 mm/yr across the Sahara Atlas fold belt between southern stations KEBI and HAMA on the African Platform and northern stations KASS in Tunisia (Fig. 4B) and CBOK – CBBR in Algeria

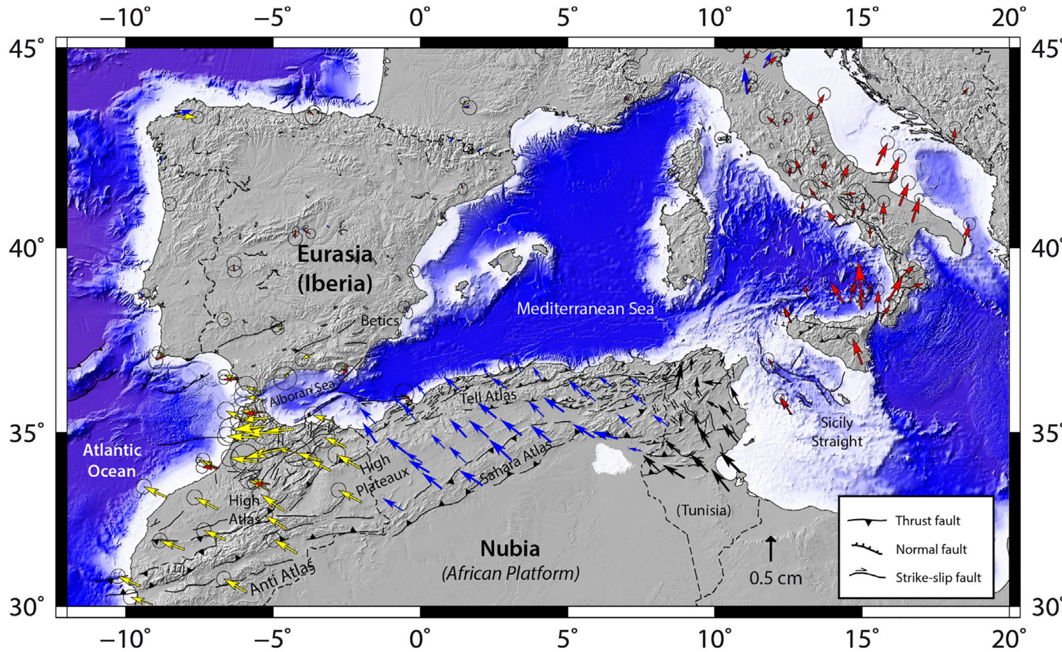

Fig. 6. Main tectonic features and GPS results (Eurasia fixed) of the Maghrebian thrust belt and related western Mediterranean geodynamics. Fault traces are from Meghraoui and Pondrelli (2012) and Meghraoui et al. (2016). In addition to the Tunisian GPS results (black velocities) from Fig. 2, we have combined solutions from Serpelloni et al., 2007 (red velocities), Koulali et al., 2011 (yellow velocities), and Bougrine et al., 2019 (blue velocities), covering the 1996 to 2018 time span. Homogenized solutions (with error ellipses of 95% confidence) result from the velocity field of GPS sites in ITRF2014 (Altamimi et al., 2016) covering the Maghrebian area in Northwest Africa in addition to the southern part of Europe. The relative velocity field is obtained using the Euler poles published by Altamimi et al. (2017) to rotate our velocity field with respect to Eurasia and Nubia fixed (see also Fig. S4). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(Bougrine et al., 2019). The Quaternary tectonics and seismicity indicate that most of the active deformation across the Sahara Atlas is taken up by E-W-trending en echelon active folding and thrusting rather than by NW-*SE*-trending right-lateral strike-slip motion. Here again, GPS velocities decrease from WNW to ESE in Fig. 4B and confirm the transpressive character with fold-related faulting across this southern section of the Maghrebian thrust belt. To the east, the Eastern Platform and the Sahel tectonic domain show low strain rates with comparable GPS velocities among stations SFAX, MZNA, SOUA and MDNA. Although the western boundary of the Eastern Platform is poorly identified, this geological domain does not include en echelon folds visible to the south in the Sahara Atlas. To the north, the reduced 1.5–2 mm/yr GPS velocities at stations KASS and KAIR and dense graben structures mark the boundary with the Central Atlas and Tell Atlas.

The GPS results in the Central Atlas and Tell Atlas show a complex pattern of active deformation with N- to NW-trending velocities except for stations BZRT and ZRBA, which show opposite E-W-trending vectors (Figs. 2 and 5). The tectonic limit between these geological domains is defined mainly by the existence of Neogene and Quaternary grabens, E-W-trending right-lateral strike-slip faults in the Central Atlas, and thrust faulting with diapir structures in the Tell Atlas. This complex geological domain requires, however, additional permanent or campaign GPS data to better constrain the kinematics and relationships between the geological domains in northern Tunisia. The maximum shortening rate appears to be accommodated across the Central Atlas and Tell Atlas.

5.2. Kinematics of Central Tunisia and Sicily Strait tectonic domain

The tectonic correlation between the eastern Maghrebide and the central Mediterranean domain includes the NW-SE-trending Quaternary graben system of continental Tunisia and the Pelagian Rift and Sicily-Calabria Arc domain correlated with the central Mediterranean tectonics (Faccenna et al., 2004). The NNW-SSE-trending grabens are remarkable tectonic features of Central Tunisia (Chihi, 1992; Ben Chelbi et al., 2013). The Quaternary graben structures are distributed in the high plateaus of eastern Algeria and the Central Atlas of Tunisia and reach the Mediterranean coastline of eastern Tunisia and the Sicily Rift zone. The WNW-NNW-trending GPS velocities and earthquake slip vectors with NNW-SSE stress and strain distributions, however, do not contradict the E-W to WSW-ENE extension of the Tunisian Central Atlas. The graben system characterizes the ENE-WSW extension in accord with the Eu-Nu NNW-trending convergence. The ENE-WSW active extension is well identified across central Tunisia in the strain distribution of Fig. 3 with an estimated 10 nstrain/yr according to GPS velocities. In our case, the extensional active deformation rate across the Sicily Rift zone is poorly estimated due to the limited number of GPS stations and relatively moderate instrumental seismicity. At the eastern end of the Maghrebian thrust belt, the estimated extension rate reaching 7 mm/yr implies an eastward increase during the Neogene across the Sicily Rift zone (Belguith et al., 2013). In contrast with Sicily, where the N-S-trending 4–5 mm/yr Eu-Nu convergence occurs principally in the Southern Tyrrhenian zone (D'Agostino and Selvaggi, 2004), the NW-SE 3–4 mm/yr Eu-Nu convergence is accommodated mainly across southern Tunisia. Hence, we may argue that the higher extension rate in the Sicily Rift zone can be associated with the ~45° clockwise rotation of GPS vectors from the Sahara Atlas to Sicily. The strain rate results with convergence rates from GPS data and active tectonics may subsequently contribute to a realistic evaluation of the seismic hazard in Tunisia and neighboring regions.

5.3. Prospect for North Africa geodynamics

The active deformation revealed by GPS velocities combined with thrust and right-lateral faulting documents the complex structure of the geological domains across the Tunisian thrust belt and illustrates the link with the oblique convergence at the Africa-Eurasia plate boundary (Figs. 5 and 6). The GPS velocities in the Maghrebian tectonic belt ranging between 2 and 7 mm/yr have a general WNW to NNW trend consistent with the active tectonics and plate convergence rate from Morocco to Sicily (Fig. 6; Serpelloni et al., 2007; D'Agostino and Selvaggi, 2004; Koulali et al., 2011; Meghraoui and Pondrelli, 2012; Bougrine et al., 2019; Meghraoui et al., 2020). The major portion of crustal deformation with transpressive movements appears to be concentrated across the Central and Southern Atlas, consistent with the earthquake distribution in these areas. The deformation field in a fixed Nubia reference frame also shows major tectonic motions in southern Tunisia and north of the African Platform (Figs. S3 and S4). Indeed, the kinematics of faulting with focal mechanisms and strain distribution illustrate the transpressive tectonics that combine E-W-trending right-lateral faulting and NNW-SSE thrust-related folding (Meghraoui and Pondrelli, 2012). The association of the WNW- to NNW-trending velocity field with slip vectors illustrated by thrust and strike-slip fault kinematics of focal mechanisms shows the consistency of the deformation field across Tunisia with neighboring regions along the Eu-Nu plate boundary (Figs. 5 and 6). The slip partitioning, mostly accommodated by tectonic structures of the southern and Central Atlas belts, indicates E-W-trending right-lateral strike-slip faulting and NE-SW- to E-W-trending fault-related folding, in agreement with the stress distribution and oblique plate convergence in the western Mediterranean (Serpelloni et al., 2007; Soumaya et al., 2018). The oblique plate convergence and transpression tectonics occur immediately north of the Sahara Platform and decrease northward in the Central Atlas and Tell Atlas.

CRediT authorship contribution statement

N. Bahrouni:Writing - original draft, Writing - review & editing, Formal analysis.**F. Masson**:Writing - original draft, Writing - review & editing, Formal analysis.**M. Meghraoui**:Writing - original draft, Writing - review & editing, Formal analysis.**M. Saleh**:Writing - original draft, Writing - review & editing, Formal analysis.**R. Maamri**:Supervision, Project administration.**F. Dhaha**:Supervision, Project administration.**M. Arfaoui**:Formal analysis.

Declaration of competing interest

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tecto.2020.228440.

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