Active Tectonics of the North Tunisian Continental Margin

Miquel Camafort1, César R. Ranero1,2, and Eulàlia Gràcia1

1Barcelona Center for Subsurface Imaging, Institut de Ciències del Mar - CSIC, Barcelona, Spain, 2ICREA, Passeig de Lluís Companys 23, Barcelona, Spain

Abstract. A poorly defined boundary between the Nubia and Eurasian plates runs along the Northern Tunisian continental margin. The Tunisia margin is deformed by a slow NW–SE trending convergence resulting in a diffuse deformation zone with scarce and scattered seismicity compared to the seismic activity into the neighboring regions to the east and west along the boundary. The area has been poorly studied and therefore its recent evolution is almost unknown, particularly offshore. Here, we present a structural analysis of the active tectonics in this submarine continental margin. The data used for this analysis are high-resolution bathymetric maps together with parametric echosounder images which have allowed to obtain a map of active faulting with unprecedented detail. The structural analysis supports a dominantly transpressive to compressive component of faulting, resulting from the current regional NW–SE trending compressive regime between plates. The North-eastern Domain of the study region contains the highest number of active faults with numerous pockmarks aligned along them. This study shows that the plate boundary across the North Tunisia margin is incipient and poorly developed, which may be due to the fact that deformation is partitioned over a large number of structures, each accommodating a small percentage of convergence, with the exception of the Hayat fault system. The Hayat reverse fault, striking WSW–ENE, is the largest fault system that comparatively may accommodate a greater amount of displacement, and is probably responsible for the uplift of the North-eastern Domain of the continental margin.

1. Introduction

The study area of the North Tunisian continental margin encompass the diffuse boundary between the Nubia and Eurasian plates (Figure 1). The region is currently in a contractual tectonic setting driven by the NW–SE plate convergence regime (e.g., Camafort et al., 2020; Serpelloni et al., 2007). The neighboring northern Algeria and northern Sicily that are comparatively better studied, currently display abundant seismicity, concordant with a compressional regime (e.g., Billi et al., 2011; Bougrine et al., 2019; Hollenstein et al., 2003; Meghraoui & Doumaz, 1996; Nocquet, 2012; Serpelloni et al., 2007; Stich et al., 2006; Totaro et al., 2016) (Figure 1). Offshore north Tunisia, the lack of seismicity and scarce seismic profiling information has prevented a detailed tectonic study.

Here, we present a structural analysis of the active tectonics in the north Tunisian continental margin. The main goal is to integrate bathymetric maps with parametric echosounder images in order to study the shallow structure of the area and to identify active tectonic structures, and determine fault style and kinematics. The result is the integration of high-resolution TOPAS profiles and high-resolution bathymetry as a fault map with unprecedented detail for the region.

2. Methodology

To characterize the offshore active tectonics, we integrated 2D parametric echosounder profiles, acquired with the Kongsberg TOPAS PS 18 sub-bottom profiler installed on-board the research vessel (RV) “Ángeles Alvarino.” High-resolution bathymetry was acquired with the ELAC Seabeam 1050D on the RV “García del Cid” and the Kongsberg EM710 multibeam echosounders on the RV “Ángeles Alvarino.” The data sets were acquired during the Geomargen-2 and Geomargen-2AA cruises in 2013. Multibeam sounds were systematically cleaned using Teledyne CARIS software and converted to depth using Vp/depth profiles daily collected during the two cruises. The high-resolution seafloor maps were composed by approximately 30 m grid node spacing, locally reaching up to approximately 10 m node spacing in the shallower regions. The survey region covers an area of approximately 15,600 km² between longitude 9°3.6′ and 11°16.6′E, and latitude 37°14.7′ and 38°41.2′N in a...
range from 18 to 2,221 m depth. More than 3.500 km of TOPAS 2D profiles were used in this work that were collected mainly in the Eastern and North-eastern Domains (Figure 2), which contain the largest number of active faults indicated by the bathymetric relief.

2.1. Criteria for Fault Classification

In order to create a systematic classification of the fault systems we defined four different groups on the basis of their seismic and bathymetric expression (Table 1):

1. Possible faults are interpreted only from geomorphologic structures because either there are not TOPAS data or seismic images do not provide valid information (e.g., regions of low TOPAS penetration).
2. Inferred faults are interpreted from coincident geomorphologic and seismic structures. Although fault offsets have not been imaged, indirect witnesses such as strata geometry (e.g., either growth strata or tilted strata) in TOPAS profiles supports recent and ongoing tectonic activity.
3. Blind faults show offsets imaged in seismic data and associated geomorphologic relief, but the fault plane does not reach the seafloor. These faults cut strata in the TOPAS images that are Quaternary and younger than approximately 1,725 kyr (lower Calabrian). Although there is a debate on the length of the time past since the last slip event occurred that is used to define active faults, it is commonly accepted that a given fault is considered potentially active if it slipped during the Quaternary (e.g., Keller & Pinter, 2002). Although the beginning of the Quaternary has been re-defined to 2.58 Ma (ICS, 2018) opening the question of the time interval to use, we interpret that the blind faults mapped in our data can be interpreted as active faults because they moved more recently than approximately 1.7 Ma. Blind fault traces are displayed in yellow in our maps and in the TOPAS profiles. In the maps, faults are classified as “main” and “secondary” depending on their dimensions.
4. Surface rupture faults are defined by both, morphological and seismic evidences. They cut the seafloor and the strata imaged on TOPAS profiles. These faults have been active during the Holocene (past 10 kyr), and are always considered active faults (Keller & Pinter, 2002). Surface ruptures in our maps and faults on TOPAS images are displayed in red color. The faults are classified as “main” and “secondary” depending on their dimensions.

In addition, recent folding in the study region is classified by its dimensions as “main” folds or “secondary” folds.

3. Tectonic Domains

Based on mapped active tectonic structures we defined three main tectonic domains (Figure 2):
1. The North-eastern Domain is bounded to the west by the Bizerte Canyon and to the south by the southern flank of the Bizerte Ridge.

2. The Eastern Domain covers the area east of the Bizerte Canyon, bounded to the north by the Bizerte Ridge.

3. The Western Domain which covers the area west of the Bizerte Canyon.

Next, we describe each of the tectonic domains.

3.1. The North-Eastern Domain

In the North-eastern Domain, bathymetry depicts elongated troughs with numerous pockmarks aligned along them. The troughs are the surface expression of fault traces that appear to have played a role controlling the up-flow migration of gas-rich fluids and consequently, the generation and preservation of pockmarks. In the North-eastern Domain fault traces average trend is N25°–N30°, and fault-associated folds are subparallel to the fault traces, and therefore their axes follow the same trend (Figures 3 and 4). In addition to the N25°–N30° main trend, some minor faults trend at N15°–N25° and N30°–N40° (Figures 3 and 4). The faults delineate a series of basin with fault-influenced deposition (Camafort, Gràcia, & Ranero, 2020).

Table 1

<table>
<thead>
<tr>
<th>Fault classification</th>
<th>Bathymetric evidence</th>
<th>TOPAS evidence</th>
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</thead>
<tbody>
<tr>
<td>Possible fault</td>
<td>Do not cut strata</td>
<td>Cut strata</td>
</tr>
<tr>
<td>Inferred fault</td>
<td></td>
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<tr>
<td>Blind fault</td>
<td>Main</td>
<td></td>
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<tr>
<td>Secondary</td>
<td></td>
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<tr>
<td>Surface rupture fault</td>
<td>Main</td>
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<tr>
<td>Secondary</td>
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Note. Classification criteria is the same for strike-slip, normal or thrust fault and the type, when interpreted, is indicated with symbols in the maps of Figures 4, 12, 17 and 18.
Fault mapping and seafloor relief delineate left-lateral pull-apart basins throughout the North-eastern Domain (Figures 3–5). The fault named Angioletta displays steep fault planes that cut the seafloor, which supports that it is currently active. The pull-apart basin geometry in map view indicates a left-lateral strike-slip fault motion (Figures 3 and 4), supported by TOPAS images (Figure 5b and 5c). North and south of the pull-apart basin (Figure 5a and 5d), the Angioletta fault changes its relative displacement from reverse to normal. This along-strike change, from normal to reverse slip, is also observed in other strike-slip faults in the area. Several NNW-SSE trending en-echelon traces observed within the North-eastern Domain, display oblique sinistral strike-slip faulting (Figures 3 and 4). The sinistral component agrees with the regional stresses inferred from the NW–SE convergence between the Nubia and Eurasia plates on this sector at the south-western extension of the Tyrrhenian Sea.

A rose diagram of fault strike shows that the approximately N30°W convergence vector is oblique to the main N25°E–N30°E faults (Figure 4).

Pure normal and reverse faults also occur in the North-eastern Domain (Figure 5b and 5c). The normal SE-dipping fault of Figure 5b and 5c cuts the seafloor, supporting recent activity. Mass transport deposits (MTDs) imaged on the hanging-wall of the normal fault, may have resulted from co-seismic shaking (Camafort, Gràcia, & Ranero, 2020). This kind of structure-less deposits and slide scars, are common features in the North-eastern Domain. A SE-dipping reverse fault named Amalia, folds and uplifts the seafloor and has syn-tectonic deposits thickening toward the east, which together with onlap terminations toward the west indicate the uplift of the western flank (Figure 6). The Amalia-fault shows slide-scars on the western flank and structure-less facies on the footwall, which affect the most recent strata (Figure 6a and 6b). These features suggest recent sliding, likely resulting from slip of the Amalia fault, which further supports recent activity. Pure normal and reverse fault slip-distribution also agrees with convergence stresses in the region. Reverse faults predominantly trend ENE–WSW, striking near-perpendicular to the main convergence vector (Figure 4). Normal faults mainly trend NNE–SSW, being highly oblique to the convergence vector (Figure 4).
Faults in the southernmost sector trend about N25°–N30° and cross the Bizerte Ridge (Figures 3 and 4). The main faults crossing the Bizerte Ridge do not cut the shallowest strata, indicating that they may be secondary to deeper faults or have not been recently active (Figure 7). The seafloor deformation supports that some deep faults are active (e.g., reverse fault at offset approximately 12,500 in Figure 7b). The main faults appear associated to troughs in the bathymetry, where steep walls of fault-scars prevent TOPAS imaging the termination of strata (i.e., main faults in Figure 7). The fault traces extend toward the north and south along a smooth seafloor, supporting that they also run along the troughs. The steepness of the faults indicates a predominant strike-slip motion, as in the northernmost areas. Comparatively, fewer reverse and normal faults occur. In general, fault trends are similar to faults in the north, with strike-slip faults changing along-strike the slip component.

The Bizerte Ridge is probably the surface expression of an anticline fold, formed above a S- to SE-directed thrust. Seismic reflection profiles show that the region of the north Tunisian margin is underlaid by a S- to SE-directed imbricated fold and thrust-belt system formed during the early-middle Miocene (Tricart et al., 1994). The Bizerte Ridge may be associated to a recently reactivated fault perhaps of the original set of thrusts. The Bizerte Ridge southeast flank displays onlap terminations and pinch-out geometries of the youngest layers indicative of contemporaneous uplift, supporting recent/ongoing fault activity (Camafort, Gràcia, & Ranero, 2020). Tilted strata likely corresponds to the forelimb of the fold creating the Bizerte ridge (Figure 8). This structural configuration supports a S-verging thrust-fault under the south-east flank of the Bizerte Ridge, that we name Hayat fault. The Hayat fault appears a regional reverse blind-thrust that likely caused the uplift of the northern sector of the study region, possibly related to a highly orthogonal fault trend to the current NW–SE convergence (Figure 4). It is 23 km long within the studied area and extends further toward the east. We do not have seismic images out from our area of study, so we can only speculate that it extends some more 20–30 km as the associated Bizerte Ridge seems to indicate.

![Image of tectonic framework](image-url)

**Figure 4.** Recent tectonic framework of the North-eastern Domain (faults and folds). The rose diagram shows the average orientation of the North-eastern Domain faults clustered in 5° groups. The white arrow shows the GPS horizontal velocity of the closer permanent station, MILO in western Sicily (Serpelloni et al., 2007), relative to the Eurasian plate. The absolute kinematic rate in MILO station is 3.5 ± 0.6 mm/yr with an orientation of approximately N30°W. Main fault systems are labeled. Location of the TOPAS profiles across the fault systems is depicted by aligned black dots (Figures 5–10).
Figure 5. TOPAS profiles showing the pull-apart basin of the Angioletta fault (a, b, c, and d). Faults with seafloor rupture are represented in red color, while blind faults are shown in yellow. Location is shown in Figures 3 and 4.
The depression next to the Bizerte Ridge shows slide scars, transparent sediment packages and tilted blocks indicative of MTDs (Figure 8). These features likely relate to uplift of the Bizerte Ridge, and may also be related to minor reverse N-verging faults (Figure 8a). Fault-related structures are more significant toward the east (Figure 8a), indicating that the Hayat fault grows toward the west (Figure 8b). Using the margin seismo-stratigraphy (Camafort, Gràcia, & Ranero, 2020) and assuming that the noncontourite strata were deposited fundamentally

Figure 6. Three parallel TOPAS profiles showing the Amalia active reverse fault (in red). Blind faults are shown in yellow color. Line location is depicted in Figures 3 and 4.
with a subhorizontal attitude, the current layering geometry supports an uplift-rate estimated as approximately 0.24 mm/yr for the last 471 kyr, due to slip on the Hayat reverse fault. Assuming a 45° dip for the Hayat fault, this uplift-rate would correspond to 0.33 mm/yr slip-rate during the last 471 kyr. This value is estimated from the strata geometrical relationship imaged on Figure 8a, thus in the western sector of the fault, where the offset is smaller than in the eastern segment, so that the slip-rate might be larger there.

Another important active feature in the North-eastern Domain corresponds to a fault system that bounds the basin H to the west (Figures 3 and 4). This system, with a NE–SW orientation, extends from the Sentinelle Valley in the north through the Bizerte Ridge in the south (Figures 3 and 4). The main fault of this system, named Valeria, cuts the seafloor and generates a wide fold, supporting recent activity (Figure 9). Seafloor morphology above the subvertical Valeria fault supports that the fold is a pressure ridge formed by the interaction of Valeria fault with secondary faults. The Valeria fault possibly dips slightly toward the east, and sediment layers thinning toward the fold indicate reverse slip on the fault (Figure 9). The activity of this fault-system in the northern and southern sectors is obscured by rougher topography, which makes difficult to determine recent activity and slip-component (e.g., faults in Figure 7). The S-shaped morphologies along the fault corridor (Figures 3 and 4) may indicate a sinistral strike-slip system, with changes in slip along-strike indicated by locally reverse-slip (e.g., Figure 9).

Numerous faults follow a similar NE–SW main regional trend along Cornaglia slope (i.e., to the south and north in Figures 3 and 4). The detailed trace of the faults is not evident due to slide scars carving the slope seafloor. These scars display a trend following the main NE-SW faulting, which supports that slides initiate along the trace of faults. A profile along the strike of the south Cornaglia slope displays comparatively little faulting, several slide scars and a smooth strata geometry, where a few subvertical fault planes with small vertical offset, cut the seafloor, and indicate strike-slip fault kinematics (Figure 10).

3.2. The Eastern Domain

The seafloor of the Eastern Domain displays few active fault traces in comparison to the North-eastern Domain. The fault lineaments associated to elongated troughs containing pockmarks described in the North-eastern Domain have no clear continuation toward the south. Similarly, tectonic structures imaged by TOPAS profiles are comparatively subdued. Few recently active tectonic structures are recognized throughout the Eastern Domain, mainly following the regional NE–SW dominant trend.
The Valeria fault system is the most significant tectonic feature, extending into the northernmost sector of the Eastern Domain. This fault corridor changes from a NE–SW orientation to a N–S trend, delineating an S-shaped bathymetric-high, that we name Snake Ridge (Figures 11 and 12). A significant normal fault together with conjugated faults and transparent deposits, possibly representing MTDs, and tilted strata, occur on the hanging-wall to the main fault, corresponding to the eastern flank of the high (Figure 13a and 13b). The MTDs support recent sudden slip of faults, although are covered by a thin undisturbed sediment veneer, indicating some elapsed time since the last fault slip causing sliding, or that the fault has not slipped since approximately 146 kyr (age derived from the seismostatigraphy; Camafort, Gràcia, & Ranero, 2020). Toward the south-west, the fault corridor may link to or dissect the Resgui Bank (Figures 11 and 12). Although the structure of the connection is not clear on the TOPAS images, seafloor relief supports a structural continuity. The S-shaped topographic high relief of the north-eastern sector of the Resgui Bank is similar to the NE–SW trending Snake Ridge, which have been described above with supporting fault control (Figures 11 and 12).

The fault corridor continues south of the Resgui Bank, where MTDs along a NE–SW trending confined depression seems to be related to a NE–SW trending significant fault-activity (Figure 13c and 13d). However, the images do not show offset strata, so that we classify them as inferred faults. The sinuous shape of the corridor within the Eastern Domain indicates a sinistral strike-slip component, similar to structures of the North-eastern Domain.

Figure 8. TOPAS profiles showing the southeastern boundary of the Hayat fault-related features. The Hayat blind-fault and other blind-faults are represented in yellow color. (a) Onlap geometries, tilted blocks, anticline, slide-scars, and chaotic facies. (b) Transparent facies are mass transport deposits (MTDs) located near slide scars. Line location is shown in Figures 3 and 4. Ages of the horizons are taken from Camafort, Gràcia, and Ranero (2020).
A major tectonic feature of the Eastern Domain is the NE–SW Samia fault, bounding the basin F to the east (Figure 11). The NW dipping Samia fault is imaged as a blind fault, although several transparent deposits at the seafloor near the Samia fault, support that it is active or was recently active (Camafort, Gràcia, & Ranero, 2020).

Figure 9. Two TOPAS profiles showing the Valeria fault (i.e., in red color, the main fault of the NE–SW fault corridor). The location of the two profiles is shown in Figures 3 and 4.

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Figure 10. TOPAS profile showing little faulting along the South Cornaglia slope. Several slide-scars disturb the regular sedimentary layering. Line location is shown in Figures 3 and 4.
Recent fault activity occurred in the basin E, where a major NE–SW trending fold has possibly been generated by slip on a reverse blind-fault named the Manahel fault (Figures 11, 12 and 14). The pinch-out of strata toward the fold and uplift of the west-central sector of the basin E, supports a reverse slip on the SE dipping Manahel fault (Figure 14). The thicker strata of the basin center is deformed by back-thrusting, which appears currently largely inactive or that slip strongly slowed down since approximately 1,116 kyr on the basis of local seismostratigraphy (Figure 14a) (Camafort, Gràcia, & Ranero, 2020). The Manahel reverse fault strikes NE–SW, and is roughly perpendicular to the regional convergence vector between the Nubia and Eurasia (Figure 4), while the associated faults mainly trend NNE–SSW, that is, oblique to the regional contractional direction.

Fault intensity further decreases southward approaching the boundary with the Western Domain, around the head of the Bizerte Canyon (Figures 11 and 12). Here, normal faulting dominates, compatible to plate convergence stresses (Figure 4). The faults near the head of the Bizerte Canyon, are possibly related to a major NNE-SSW trending fault, underlaying the main canyon (Figure 11), which possibly are active, as indicated by strata offsets under the canyon (Maldonado & Stanley, 1976). This normal fault displacement probably has a current left-lateral strike-slip component, compatible to the regional compressional vector (Figure 11), and supported by vintage seismic imaging (Compagnoni et al., 1989).

Fault-controlled evolution of the sediment depocenter supports a recent tectonic activity in basin B (Camafort, Gràcia, & Ranero, 2020). Growth-strata thinning toward the eastern sector and fold development support active uplift by reverse faulting (Figures 11, 12 and 15). The core of the fault-controlled active folds appears to contain...
old strata folded in a previous unconstrained contractional regional tectonic phase (Figure 15). The faults located within basin B are subvertical and the strata display little tilting, which supports a sinistral strike-slip fault component within the regional N30°W convergence (Figures 11 and 15). Inferred and possible E–W-trending faults occur in the south-eastern sector of the Eastern Domain, north of the Hecate bank, although their structure is poorly imaged in the data (Figures 11 and 12).

3.3. The Western Domain

The Western Domain displays comparatively little evidence of tectonic activity. We used geomorphological features to interpret the tectonic features, as only few TOPAS profiles were collected in this region (Figure 2), so that only possible faults are displayed (Figures 16 and 17). Relief lineaments trending NE–SW to the NW of the Sentinelle Bank may be potential fault-traces. These lineaments follow the NE–SW fault trend of the main strike-slip faults on the other domains. The geometry of the lineaments link the eastern flank of the Sentinelle Bank to the Estafette Bank, which suggest a fault system following NE–SW and NW–SE trends that might be related to the major fault under the Bzerte Canyon (Figures 16 and 17).
Figure 13. TOPAS profiles showing the NE-SW corridor within the Eastern Domain. TOPAS profiles (a) and (b) showing the north-eastermost sector and (c) and (d) the south-westernmost one. Transparent facies are mass transport deposits (MTDs). Layers tilted by faults are also depicted. In yellow color are represented the blind faults, while in white are shown the Inferred faults. Location is shown in Figures 11 and 12. Ages of horizons are shown in Figure 8b and taken from Camafort, Gràcia, and Ranero (2020).
4. Discussion

The map of recent tectonics (Figure 18) shows that active faults (i.e., Surface Rupture Faults and Blind Faults, respectively) are mainly located within the eastern domains of the study region, and particularly in the North-eastern Domain. Blind faults occur on both domains and surface rupture faults are largely restricted to the North-eastern Domain.

Figure 14. TOPAS profiles showing the folding and blind faulting within the basin E. The Manahel Blind reverse fault is depicted. The location of the profiles is shown in Figures 11 and 12. Ages of horizons are shown in Figure 8b and taken from Camafort, Gràcia, and Ranero (2020).

Figure 15. TOPAS profiles showing the faulting within the basin B. Smooth folding and growth strata are identified. In yellow color are represented the blind faults, while in yellow dashed lines are shown the Possible faults. Strata geometry and unconformities define two phases of folding. Location is shown in Figures 11 and 12.
The North-eastern Domain shows most of the blind and surface rupture faults within the study region with the latter being mainly located at the north-easternmost sector of this domain. Faults within this domain mainly trend NE–SW, forming small NNW–SSE pull-apart basins aligned forming en-echelon geometries, bounded by subvertical fault planes with a main oblique sinistral strike-slip component (Figures 5 and 18). Strike-slip faults tend to change from oblique normal segments to oblique reverse segments. The ENE–WSW trending faults typically show reverse component (Figure 18), while NNE–SSW trends dominantly have normal component (Figure 18). The ENE–WSW trends are perpendicular to the main convergence vector (i.e., rose diagram in Figure 4), while the NNE–SSW trends tend to be oblique to the convergence vector (Figure 4). These observations are consistent with the present-day plate regional NW–SE contractional stress-field (e.g., Serpelloni et al., 2007), displaying a transpressive regime. The North-eastern Domain, containing most active faults, occurs across the recently uplifted area (i.e., at least since 0.402 ± 5 Ma, see Camafort, Gràcia, & Ranero, 2020), which supports that current tectonics focus on the North-eastern Domain. Faulting within this domain shows a preferential SE dip, with the exception for faulting at the south-eastern boundary of the Bizerte Ridge (Hayat fault) that dips toward the NNW (Figure 18).

The Eastern Domain does not display surface rupture faults and blind faults occur in a comparatively scattered and sparse distribution (Figure 18). The main fault trend is NE–SW direction, similar to the systems in the North-eastern Domain. Numerous faults have associated MTDs, particularly in the main fault corridor (Figures 13 and 18) and within basin F (Figure 18). Blind faults deforming the seafloor occur within basins E and B. Basin E faults
display pure NE–SW reverse kinematics and NNE–SSW back-thrusts concordant with the regional stress field. In contrast, basin B shows strike-slip faults and west-dipping reverse faults that uplift the eastern basin edge. Minor faults at the head of the Bizerte canyon might be related to the major fault underlying Bizerte Canyon, which may currently have a sinistral strike-slip component, matching the current N30°W contractional regime. In contrast to the North-eastern Domain where faulting generally dip toward the E or SE, the Eastern Domain contains E or SE dipping faults and opposite NW dipping faults (i.e., basins F and B).

The relief map supports that the NE-SW trending faults of the North-eastern Domain extend north of our high resolution map, into the Tyrhenian Basin (Figure 18). Faults trending NE–SW and dipping preferentially toward the south-east have been imaged on deep-penetrating seismic images along the south-western region of the Tyrrenhian, across the north Sicily Margin (Figure 19; Guzman, 2015; Prada et al., 2016). These faults form horsts and grabens associated to the opening of the Tyrrenhian Basin. North of our study area, these faults dip eastward, indicating that the shallow SE-dipping active faults, identified in the North-eastern Domain and northern sector of the Eastern Domain, might be extensional faults formed during Tyrrenhian opening (Loreto et al., 2020; Prada et al., 2020) about approximately 8–6 Ma (Mascle & Rehault, 1990; Trincardi & Zitellini, 1987). These previously normal faults are currently being inverted on a transpressional system in the frame of the present NW–SE convergence between the Nubia and Eurasian plates (Figure 4). Undifferentiated Plio-Quaternary minor phases of inversion and recent compressive folding have been described along the edge of the Tunisian plateau in the

Figure 17. Interpreted shaded relief map of the Western Tectonic Domain. Framework of the recent tectonic structures in the Western tectonic Domain.
Figure 18. Recent tectonics of the North Tunisian continental margin. Epicenters of magnitude Mb between 3 and 6 are from the International Seismological Centre (ISC, 2018). The main tectonic domains are bounded by the three white polygons. Dashed black line depicts the boundary between Algeria and Tunisia. SF: Samia fault, HF: Hayat fault, VF: Valeria fault, BCF: Bizerte Canyon fault.

Figure 19. Interpreted multichannel seismic (MCS) profile across the North Sicily margin taken from Guzman (2015). Recent faults and seismo-stratigraphic sequence, from Pleistocene to Tortonian are depicted. Inset: Colored bathymetric map of the North Tunisian Margin with the location of the MCS profile in a black line (SAR, Sardinia; SIC, Sicily; TUN, Tunisia).
Sardinia Channel area (Mascle et al., 2001, 2004; Tricart et al., 1990, 1994) and is active in the Tyrrhenian Basin (Sulli et al., 2021; Zitellini et al., 2020).

The south Tyrrhenian active contractional belt trending E–W north of Sicily (i.e., to the east of the North-eastern Domain, Figure 18) is inferred to be segmented by a succession of ENE–WSW and NE–SW trending reverse faults, and NW–SE right-lateral strike- and oblique-slip faults (Billi et al., 2007). Based on focal mechanisms, the ENE- to NE-striking faults are proposed to be high-angle south verging reactivated inherited faults (Billi et al., 2007). The Hayat fault (Figure 18), along the south-eastern flank of the Bizerte Ridge, displays a pattern that supports reactivation of an inherited NW-dipping fault. Thus, the ongoing convergence between Nubia and Eurasia, possibly reactivates either transtensional or transpressional strike-slip faults that originally were generated during the opening of the Tyrrhenian Basin (i.e., SE-dipping, NE-SW trending faults of the North-eastern Domain). Likewise, the NW-dipping NE–SW trending faults of the North-eastern and Eastern domains may correspond to the reactivation of older faults from the fold-and-thrust belt system, formed in the African margin during the opening of the Algeo-Balearic Basin at approximately 17–14 Ma.

The estimated approximately 0.33 mm/yr slip-rate for the Hayat fault during the last 471 kyr is significantly larger than the slip of any other NE–SW reverse fault, all with smaller offsets, of the North-eastern Domain. The highly orthogonal attitude of the Hayat fault with respect to the Nubia-Eurasia convergence vector and strongly tilted strata at the forelimb of the Bizerte Ridge, suggests that Hayat fault is likely a major fault accommodating much of the convergence between the plates on the studied area (Figure 4). Furthermore, slip on the Hayat fault appears to control the topographic evolution of the northern sector, and is responsible of its uplift (Camafort, Gràcia, & Ranero, 2020).

Several seismo-tectonic and geodetic studies propose that the current approximately 5 mm/yr convergence between the Nubia and Eurasian plates in the central Mediterranean is currently being completely or largely absorbed across the southern Tyrrhenian seismic belt (Figure 1) (Billi et al., 2011; Goes et al., 2004; Nocquet, 2012; Serpelloni et al., 2007; Totaro et al., 2016). Along Algeria, the current approximately 2–3 mm/yr of convergence are accommodated in a narrow belt along the north-Algerian margin (Figure 1; e.g., Bougrine et al., 2019; Meghraoui & Doumaz, 1996; Serpelloni et al., 2007; Stich et al., 2006). In our study area, it appears that a considerable amount of the total convergence is being accommodated by the Hayat fault, although we have not being able to calculate its cumulative strain. However, the region to the east of our survey area displays poorly quantified deformation that has some seismicity associated (Figure 18) and may contain unmapped active tectonic structures.

Serpelloni et al. (2007) noted that the residual shortening of the 2.3 ± 0.5 mm/yr NW-ward drift of Sicily has to be accommodated between Ustica (in NW Sicily) and the Corsica-Sardinia block, that is, N-NE of our study region. Due to the lack of instrumental seismic events along this region, Serpelloni et al. (2007) suggest that compression is probably transferred northwards, in Liguria, where active thrusting has been described (e.g., Bigot-Cormier et al., 2004; Larroque et al., 2001). Although some convergence might be absorbed in Liguria, our study supports that part of the shortening is accommodated within our study region, mainly by the Hayat fault and across the North-eastern Domain sinistral fault system. The main NE-SW trending sinistral strike-slip system in a transpressive regime defined in our study area differs from the faulting in northern Sicily and Algeria. There, both areas display compressional regimes with prevailing thrust focal mechanisms (e.g., Billi et al., 2011; Serpelloni et al., 2007).

5. Conclusions

The structural analysis of high-resolution seafloor maps and TOPAS images reveals for the first time multiple active fault systems defined in the in the north Tunisian continental margin. The tectonic structures display variable expressions in the data which has led to a classification in four groups based on their characteristics that refers to the certainty on their presence and in their current activity. Surface Rupture Faults display both morphological and seismic features and offset to the seafloor. They are active during the Holocene (0.1 Ma) and considered currently active faults. Blind Faults offset strata at depth and have associated seafloor relief, but they do not cut the seafloor. They cut strata younger than approximately 1,725 kyr (lower Calabrian) and can be considered active faults. Inferred faults involve seafloor morphologic and seismic structures. Faults do not offset strata in images but their geometry (e.g., growth strata or tilted strata) supports recent tectonic activity. Possible faults are interpreted from seafloor relief structures because either we do not have profiles or the imaging is poor.
The North Tunisia continental margin fault systems dominantly show a transpressive to compressive component, resulting from the current NW–SE plate convergence compressive regime. Based on the density and significance of active tectonic structures, we defined three main tectonic domains. The North-eastern Domain is located in the transition from the Tyrhenian basin to the North Tunisia margin, and it is bounded to the west by the Bizerte Canyon and to the south by the southern flank of the Bizerte Ridge. The North-eastern Domain contains the highest number of active faults, the largest and longest fault systems, and the greatest fault-associated relief. The largest fault systems form lineaments that contain numerous pockmarks along them, possibly related to recent fluid expulsion. The largest fault systems form sigmoidal seafloor highs containing uplifted consolidated sediment. Further south, extends the Eastern Domain, covering the area east of the Bizerte Canyon and bounded to the north by the Bizerte Ridge, and to the south by the narrow continental shelf. A few fault systems extend from the north into this domain, although fault density decreases abruptly. The Western Domain covers the area west of the Bizerte Canyon, which contains only few seafloor morphologies that may indicate recent faulting, while most of it displays a dominantly smooth seafloor.

Most surface rupture and blind faults (i.e., active faults) occur within the North-eastern Domain. These faults are mainly SE-dipping NE–SW trending faults, possibly originally formed during the opening of the Tyrhenian Basin segment to the north at approximately 8–6 Ma. Currently, they are reactivated with strike-slip displacement and inverted in compression due to plate convergence. The kinematic indicators of the faults of the North-eastern Domain support a transpressional regime with a main sinistral strike-slip faulting style. Faults dipping NW and trending NE–SW are related to the older fold-thrust belt system, formed during the early-middle Miocene, during the opening of the Algeo-Balearic basin. Some of these faults are also reactivated with different fault kinematics, such as reverse faults in basin B and normal faults in basin F. The largest fault system is the WSW-ENE Hayat reverse fault, located south of the Bizerte Ridge. This structure is likely accommodating much of the plate convergence within the studied area. The recent slip of Hayat fault appears also responsible for the uplift of the North-eastern Domain.

Thus, the plate boundary deformation across the North Tunisia margin is incipient and partitioned over a large number of structures, each accommodating a comparatively small percentage of convergence, with the exception of the Hayat fault system that, relatively, may accommodate a larger amount of displacement. This broad zone of deformation may also explain the lack of instrumental seismicity in the study area. Some of the deformation might be occurring to the East of our study area yet undetected in the poorly studied East Tunisia continental margin.

Data Availability Statement
The original seismic images and maps used for this publication are available online (at https://doi.org/10.5281/zenodo.6350585).

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