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Plio–Quaternary Tectonic Activity in the Northern Nubian Belts: The Main Driving Forces

Enzo Mantovani, Marcello Viti *, Daniele Babbucci and Caterina Tamburelli

Dipartimento di Scienze Fisiche, della Terra e dell'Ambiente, Università di Siena, 53100 Siena, Italy; enzo.mantovani@unisi.it (E.M.); babbucci@unisi.it (D.B.); tamburelli@unisi.it (C.T.)

* Correspondence: marcello.viti@unisi.it

Abstract: It is suggested that the occurrence of tectonic activity in the northern Nubian belts (Tell-Rif and Atlas systems) since the Late Pliocene can be interpreted as one of the processes that were produced in the central and western Mediterranean zones by the collision of the Adriatic continental promontory with the Anatolian–Aegean Tethyan system. Since then, the consumption of the residual low-buoyancy domains in the Mediterranean area was allowed by a major change in the plate mosaic and the related kinematics. The new tectonic setting started with the decoupling of a large portion of the Adriatic domain (Adria plate) from Nubia, through the formation of a long discontinuity crossing the Ionian domain (Victor Hensen–Medina fault) and the Hyblean–Pelagian domain (Sicily channel fault system). Once decoupled, the Adria plate underwent a clockwise rotation, at the expense of E–W shortening in the Hyblean–Pelagian domain and in the northern Nubian margin. The shortening in the Pelagian domain was accommodated by the northward escape of the Adventure wedge, which in turn caused the northward displacement of the eastern Maghrebian sector. The indentation of these structures into the Alpine–Apennine material lying east of the Corsica–Sardinia block induced an east to southeastward escape of wedges (southern Apennines and Calabria). This occured at the expense of the remnant Ionian Tethys oceanic domain and the thinned Adriatic margin. The extensional regime that developed in the wake of the migrating wedges led to the formation of the central and southern Tyrrhenian basins. In the northern Nubian belts, the westward push of the Adria–Hyblean–Pelagian domain has been accommodated by oroclinal bending, thrusting and uplifting across the Tell and Atlas belts. This geodynamic context might explain some features of the seismicity time pattern observed in the Tell system.

Keywords: Atlas and Tell belts; tectonics; geodynamics; Plio–Quaternary

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Academic Editor: Roberto Scarpa

Received: 12 November 2024
Revised: 19 December 2024
Accepted: 31 December 2024
Published: 9 January 2025

Citation: Mantovani, E.; Viti, M.; Babbucci, D.; Tamburelli, C. Plio–Quaternary Tectonic Activity in the Northern Nubian Belts: The Main Driving Forces. *Appl. Sci.* **2025**, *15*, 587. https://doi.org/10.3390/app15020587

1. Introduction

The northern margin of the Nubian plate consists of the Tell-Rif and Atlas belts and the internal Sahara platform (Figure 1). The Atlas system includes an eastern (Tunisian) sector, a central (Algerian Sahara) sector and a western (Moroccan) sector, usually referred to as the Middle and High Atlas. It also encompasses the Tunisian Pelagian domain (Sahel), the Algerian High Plateau and the Moroccan Meseta, which are remnants of Paleozoic belts often covered by Mesozoic carbonate platforms, only slightly deformed by the Atlas orogeny (e.g., [1]). The Atlas system was thrust over the Sahara platform foreland along the South Atlas Front and primarily deformed during two key tectonic phases. The first developed between the Middle Eocene and Early Miocene (Aquitanian) and the second since the Pleistocene, involving the entire Nubian margin (e.g., [2–5]).

The Tell system, comprising the Algerian–Tunisian sectors of the Maghrebides, consists of metamorphic units (Kabylides or internal Tell) and an accretionary belt (external Tell), formed by the trench arc-back arc process that created the Balearic basin (e.g., [2,5–11]). This process concluded around the Serravallian–Tortonian, when the southward migrating arc (Kabylides–Tell) collided with the Nubian continental domain, leading to the suture of the consuming boundary and the subsequent disruption of the related slab [2,5,12]. This suture was followed by a phase of tectonic quiescence in both belts until the Pleistocene, when the entire northern Nubian margin underwent a new tectonic phase, involving the thrusting, uplifting and inversion of normal faults [2,5,12–17]. Compressional deformation continues along the northern Nubian belts, as evidenced by onshore and offshore geomorphic features and seismic activity (e.g., [16,18–25]). The active faults indicate ongoing underthrusting of the Neogene oceanic domain beneath the Algerian margin (e.g., [2,26,27]).

The driving force behind the Pleistocene tectonic phase remains a topic of debate. The location of the Atlas–Tell system has strongly supported the hypothesis that the deformation of these belts was driven by the Nubia–Eurasia convergence (e.g., [28–32] and references therein). However, a significant issue with this interpretation is explaining why this presumed force had minimal effects during the preceding extended time period. Such scenario would imply a rather discontinuous motion of Nubia, which is not supported by the deformations that occurred along other plate boundaries. Additionally, it raises questions about how the supposed plate convergence accounts for the complex spatio-temporal distribution of the Plio–Quaternary tectonic processes in the central Mediterranean area [7–11], including the development of major discontinuities in the Ionian and Pelagian zones, the marked northward displacement of the Maghrebian belt, the southeastward extrusion of the southern Apennines and Calabrian wedges and the formation of the Campidano trough in Sardinia. Some have attempted to address this issue by proposing additional driving forces, such as slab-pull and other subduction-related mechanisms (e.g., [33–36]). However, these geodynamic interpretations struggle to account for major pieces of evidence (e.g., [8,9,11]).

Regarding the current tectonic setting, the focal mechanisms and neotectonic structural data in the Atlas and Tell belts indicate that this zone is experiencing dextral shearing, thrusting and uplifting (e.g., [37–39]). This regime further challenges the notion that the zone is simply stressed by the Nubia–Eurasia plate convergence.

In the next section, it is argued that the geodynamic context that can plausibly account for the central Mediterranean tectonic processes (e.g., [9]) may also explain the Plio–Quaternary deformation observed in the northern Nubian belts.

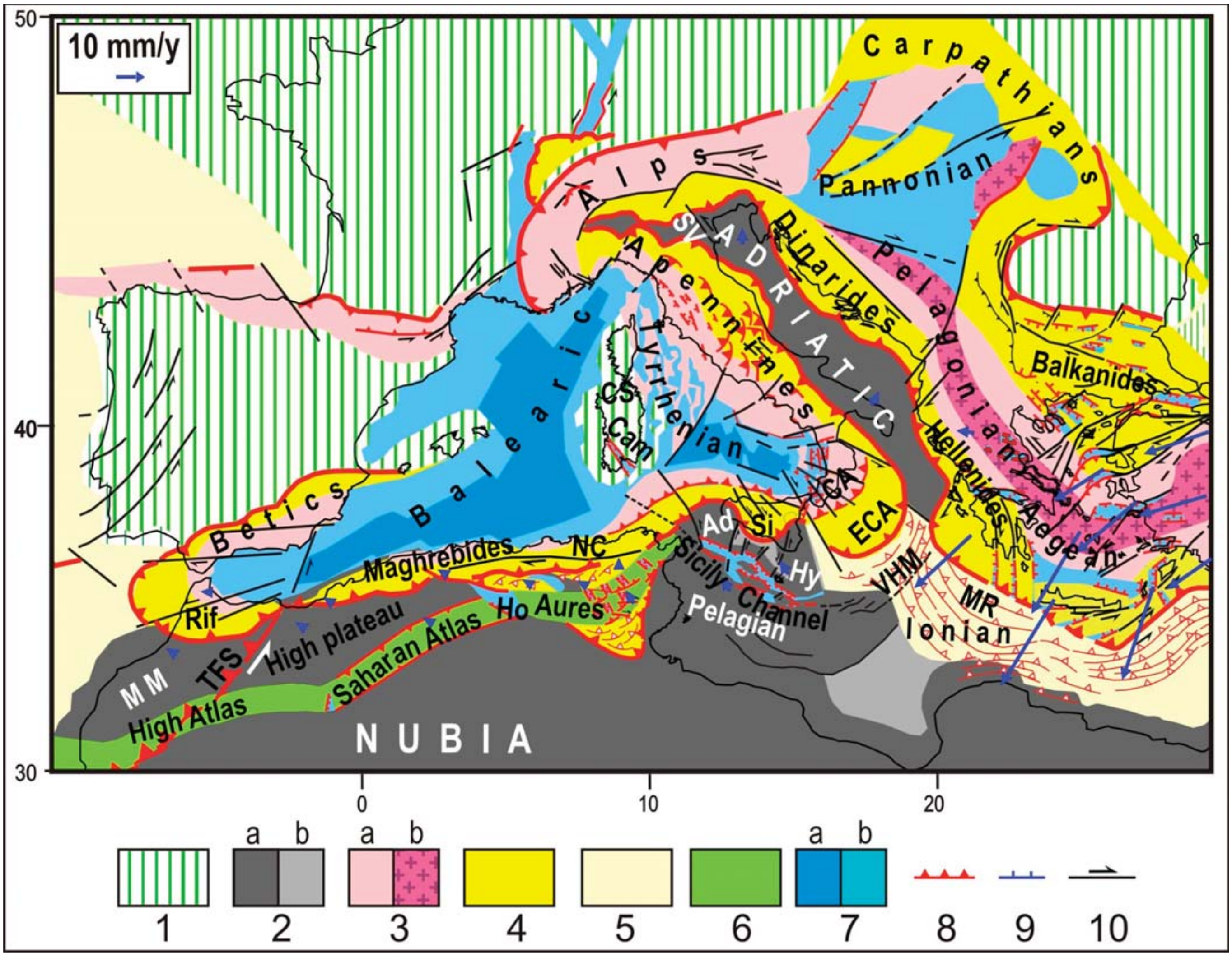


Figure 1. Tectonic sketch of the central and western Mediterranean regions. (1) Continental Eurasian domains, (2) continental (a) and thinned continental (b) African/Adriatic domains, (3) Tethyan belt constituted by ophiolitic units (a) and metamorphic massifs (b), (4) other orogenic belts, (5) old oceanic domains, (6) Atlas belt, (7) zones affected by intense (a) or moderate (b) crustal thinning, and (8, 9, 10) compressional extensional and strike-slip tectonic features. Blue arrows indicate the present kinematic pattern with respect to Europe, mainly based on geodetic observations (e.g., [40,41]), considering that this kinematic pattern has been strongly influenced by the post-seismic relaxation triggered by the seismic sequence that developed along the north Anatolian fault since 1939 [9,42,43] (see Section 3 for explanations). Ad = Adventure wedge, CA = Calabrian arc, Cam = Campidano graben, CS = Corsica–Sardinia block, ECA = external Calabrian arc, Ho = Hodna basin, Hy = Hyblean plateau, MM = Moroccan Meseta, MR = Mediterranean ridge, NC = north Constantine fault, Si = Sicily, SV = Schio-Vicenza fault, TFS = Transmoroccan fault system, VHM = Victor Hensen–Medina fault system.

2. Geodynamics and Tectonics in the Central and Western Mediterranean Region Since the Middle Miocene

In the Middle–Upper Miocene (Figure 2a), tectonic activity in the eastern Mediterranean region (involving the westward displacement and bending of the Anatolian–Aegean–Pelagonian Tethyan belt) was primarily driven by the northward indentation of the Arabian promontory [44–47] and the consequent westward escape of Anatolia. In the central and western Mediterranean zones, the outward migration and bending of the Alpine–Apennine and Alpine–Maghrebian belts, at the expense of the Alpine Tethys domain, were driven by the Nubia–Eurasia convergence. The extension that developed in the wake of the migrating belt led to the formation of the Balearic basin [8–11]. During this phase, the convergence between the eastern and central–western Mediterranean systems encountered limited resistance, as it was predominantly accommodated by the consumption of the interposed thinned continental domain (Ionian zone), situated between the thickened Pindos and Pre-Apulian belts [48–53]. During this consuming process, the sedimentary cover of the Ionian zone was scraped off the descending crust, facilitated by the presence of an interposed layer of Triassic evaporites, and accumulated in the trench zone (e.g., [54]). This led to the accretion of light crustal material, as indicated by the Hellenides thrust-and-fold system cropping out in Albania and northwestern Greece (e.g., [55,56]), progressively increasing the resistance to horizontal shortening.

These relatively independent eastern and western tectonic contexts persisted until the Late Miocene–Early Pliocene, when the Aegean sector of the Tethyan belt collided with the Adriatic continental domain [57,58]. The suture of that consuming boundary significantly increased resistance to further convergence of the colliding systems. This context gradually induced the activation of a new large-scale shortening pattern, aimed at consuming the remaining, thinnest low-buoyancy zones in the Mediterranean area (Figure 2c). In the eastern Mediterranean, the resistance of the Adria plate accelerated the southward bending of the Anatolian and Aegean sectors of the Tethyan belt, at the expense of the Levantine and Ionian oceanic domains [44–47].

In the central and western Mediterranean, the reorganization of the tectonic context was far more drastic. Under the influence of the westward push of the Anatolian–Aegean Tethyan belt, a significant portion of the Adriatic promontory (here after referred to as Adria plate) decoupled from Nubia. This occurred via the formation of a long fracture through the Ionian domain (Victor Hensen–Medina fault, e.g., [59–61] and references therein, [62]) and the Hyblean–Pelagian zone (Sicily channel fault system, e.g., [63–65]). Decoupling of Adria also occurred from its northwestern edge (Padanian) through the reactivation of an old fault zone (Schio-Vicenza e.g., [8,9,11,66–69]). Following these decouplings, the Adria plate underwent a clockwise rotation and a minor north–northwestward motion (Figure 2b). The westward motion of southern Adria induced a strong E–W compression in the Hyblean–Pelagian domain and along the northern Nubian margin. The consequent shortening of the Hyblean–Pelagian domain was mainly accommodated by the northward extrusion of the Adventure wedge and the displacement of the easternmost Maghrebian sector. The northward indentation of these structures into the Alpine–Apennine material lying east of Sardinia caused the east to southeastward escape of wedges (southern Apennine and Calabrian units), at the expense of the Tethys oceanic remnants and the thinned margin of Adria [9,10,70,71]. The extensional deformation that developed in the wake of the migrating Apennine and Calabrian units, generated the central and southern Tyrrhenian basins, while new accretionary belts developed along the fronts of the migrating wedges [7–11].

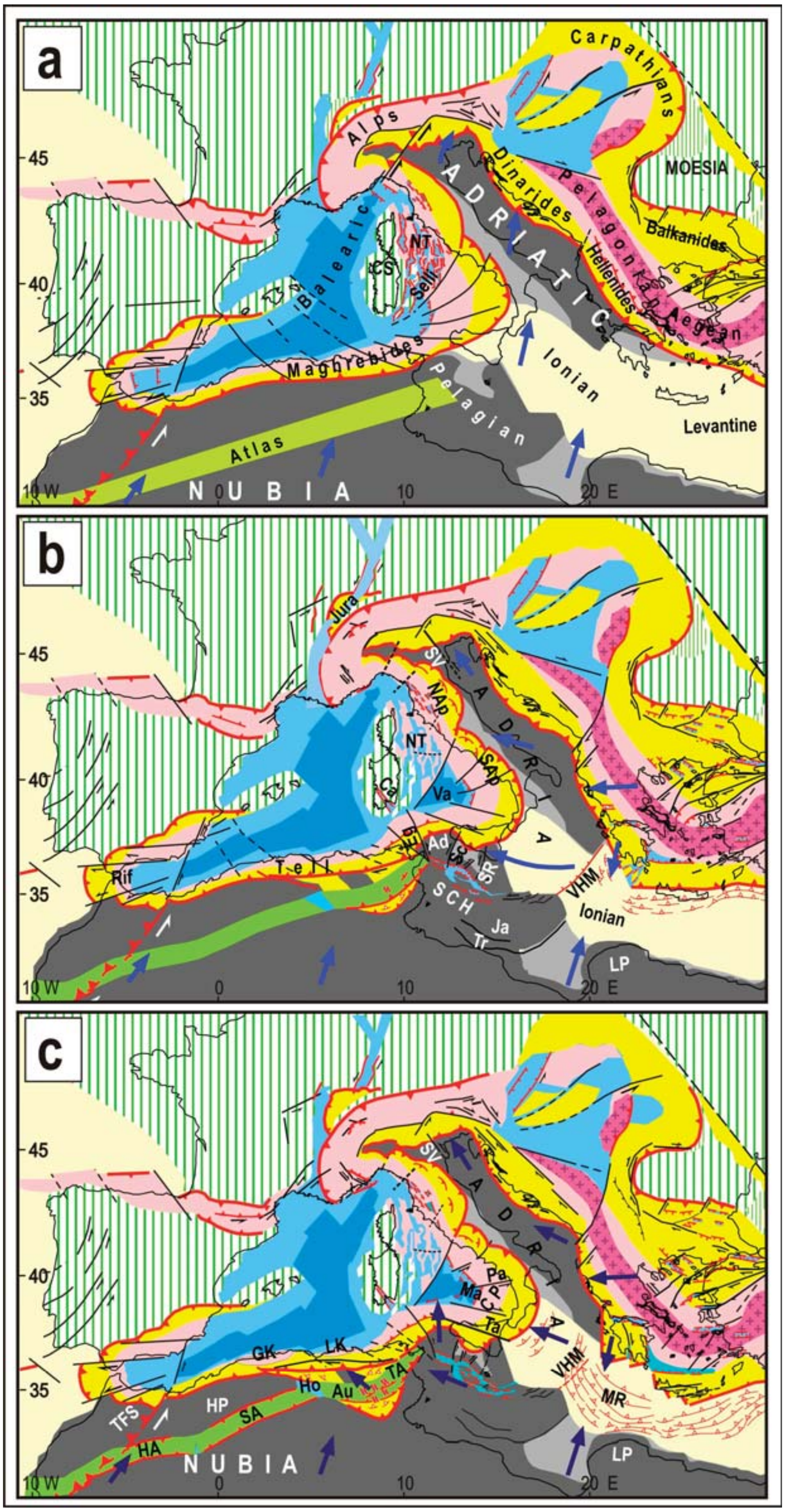


Figure 2. Neogenic evolution of the central and western Mediterranean regions. (**a**) Late Miocene, NT = northern Tyrrhenian. (**b**) Middle–Late Pliocene. Eg = Egadi fault, Ja = Jarrafa fault, LP = Libyan promontory, NAp = northern Apennines, SAp = southern Apennines, Sc = Sciacca fault, SCH = Sicily channel, SR = Scicli-Ragusa fault, SV = Schio-Vicenza fault, Tr = Tripolitania fault, Va = Vavilov basin, VHM = Victor Hensen–Medina fault. (**c**) Pleistocene. Au = Aures, CP = Calabria–Peloritani wedge, GK = Greater Kabylia, HA = High Atlas, HP = High Plateau, LK = Lesser Kabylia, Ma = Marsili basin, MR = Mediterranean ridge, Pa = Palinuro fault, SA = Saharan Atlas, TA = Tunisian Atlas, Ta = Taormina fault, TFS = Transmoroccan fault system. See the text for explanations. Arrows indicate the long-term kinematic pattern [9,11,72]. Colors, symbols and other abbreviations as in Figure 1.

The northward indentation of the Adventure wedge and the Maghrebian units also stressed the eastern Corsica–Sardinia block, leading to the formation of the Campidano graben in Sardinia [8,9,11,73–75], a tectonic event that can hardly be attributed to alternative driving forces.

In the northern Nubian margin, the westward push of the southern Adria plate caused oroclinal bending, thrusting and uplifting in the Tell and Atlas belts (Figure 3). The eastern sector of these chains (Tunisia) experienced the most significant deformation, including the formation of several SW–NE anticlines in the Aures zone (Figure 3b,c, e.g., [2,18,24,29,76–78]). It can be noted that these features are perpendicular to the combined motions of the Nubian plate (north–northeastward) and of the Pelagian domain (westward). The deformation of the Aures zone also involved the development of several NW–SE oriented troughs (e.g., [2], Figure 2c). This deformation can be attributed to the SW–NE extension that occurred in the wake of the Maghrebian belt sector, which was pushed northward by the Adventure wedge (Figures 2c and 3b).

The intense deformation that the easternmost Atlas sector underwent during this phase may explain why that chain is now very close to the Tell belt. This hypothesis is supported by paleogeographic studies, which suggest that a platform existed between the Atlas basin and the Tell passive margin ([2] and references therein). This platform, referred to as the “Neritic Constantine units” [79] in Algeria and the “folded foreland” in Tunisia [80], is now allochthonous and has been integrated into the Tell thrust belt [79]. Immediately south of this shelf, the Atlas Meso-Cenozoic basin was particularly deep in the Aures and the Tunisia trough [2], constituting a zone of crustal weakness, which has been affected by tectonic inversion since the Pliocene [76,81,82]. The fact that the Hodna basin is located in the Atlas sector affected by the maximum curvature (between the Aures and the Saharan segments, Figure 3b) is unlikely to be a mere coincidence.

The combined westward motion of Adria and the north–northeastward motion of Nubia can explain the right lateral transpressional strain regime in the Tell, evidenced by strike-slip faults and thrust fronts onshore and offshore. These deformations are particularly evident in the Tell zones surrounding the Kabylides (e.g., [2,16,32]).

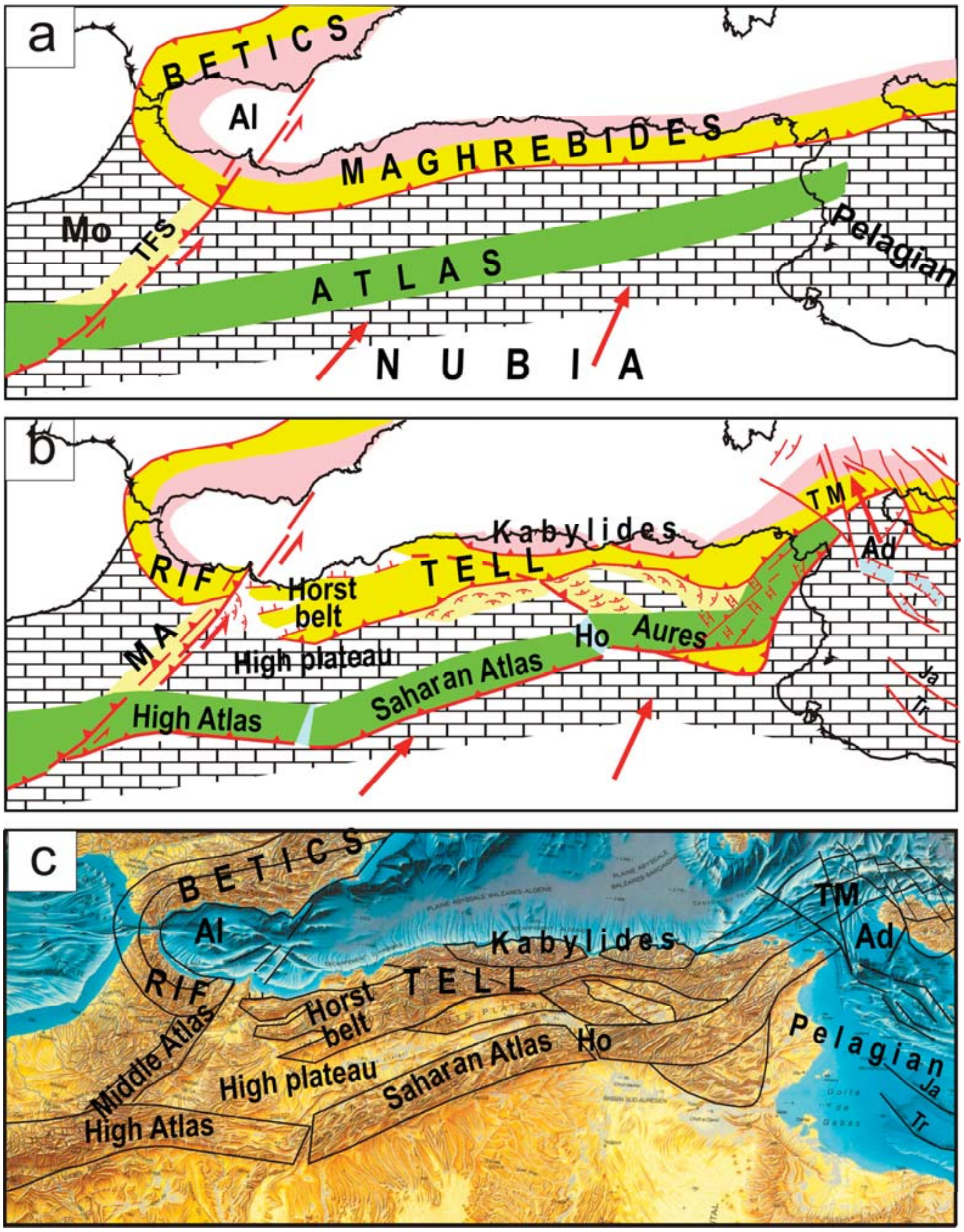


Figure 3. Tentative reconstruction of the Plio–Quaternary deformation pattern of the northern Nubian belts, driven by the westward motion of the Pelagian domain and the north–northeastward motion of Nubia with respect to Eurasia (red arrows). (**a**) Early Pliocene. Al = Alboran wedge, Mo = Morocco block, TFS = Transmoroccan fault/fold system. (**b**) Late Pleistocene. Ad = Adventure wedge, MA = Middle Atlas, Ja = Jarrafa fault, Ho = Hodna basin, SCH = Sicily channel, TM = Tyrrhenian Maghrebides, Tr = Tripolitania fault. (**c**) Contouring of the main Atlas and Tell belts, in the morphological map of [83], considered in the evolutionary reconstruction of Figures 2 and 3. See the text for explanations. The red arrows show the motion of Nubia and the Adventure wedge with respect to Eurasia [9,72]. Symbols and colors as in Figures 1 and 2.

If the central sector of Atlas (Saharan) has indeed experienced the southward bending tentatively illustrated in Figure 3b,c, an S–N extension might be expected in the region between the Atlas and the Algerian Tell. This extension may also have influenced the western segment of the Tell, causing the development of the basin and range structure, visible on the morphological map (Figure 3c) and the geological features in the so-called "Horst belt", located near the Algeria–Morocco border (e.g., [22]). This area is characterized by linear WSW–ENE mountain ridges separated by large basins (e.g., [21,84]). It is worth noting the presence of conspicuous deposits of Pliocene–Quaternary alkaline basalts and basanites in some of the above basins (e.g., [85–88]). Such volcanism would suggest that an extensional or trans-tensional stress regime has affected the Horst belt since the Pliocene [84]. Further studies [89] suggest that in the most recent evolution, this zone has undergone a compressional and/or transpressional tectonics.

The presence of Triassic evaporites in the crustal structure of the Nubian belts [90–93] may have favored the decoupling of the upper crustal units from their basements. This mechanism has also been recognized in other migrations of orogenic belts, such as the Apennines belt [7–9,11,94–99] and the Albanides–Hellenides (e.g., [54,100]).

The convergence between western Nubia and the Iberian block, with the Alpine–Iberian units (Betics and Rif) in between, shaped the deformation pattern in the High and Middle Atlas. In the first collisional phase, these zones were affected by thrusting and uplifting [89,101,102], accompanied by a transient slowdown of western Nubia (due to the resistance of the Iberian block). During this phase sinistral shear stress was increasing between the main Nubia plate and its (resisted) northwesternmost edge. When this stress increase reached a critical stage, the formation of a major SW–NE transpressional fault system (Transmoroccan) allowed the decoupling of Nubia from the Moroccan plate (Figure 2c, [8–11,71,103–107]). This decoupling allowed western Nubia to gradually recover its previous motion rate.

Crustal and subcrustal seismicity (e.g., [108,109]), and abundant Pliocene–Quaternary alkaline basaltic volcanism (e.g., [85,110–113]), provide evidence of the ongoing tectonic activity at the Transmoroccan discontinuity [108,109]. Lithospheric thinning from the High Atlas to the Rif (Moroccan hot line in [12]) is indicated by the geophysical profiles. The occurrence of left lateral transpression along the Transmoroccan fault system is compatible with the focal mechanism of the strong earthquake that occurred along this fault system on 8 September 2023 (M = 6.8), at a depth of approximately 30 km (USGS, https://earthquake.usgs.gov accessed on 1 September 2024). The analysis of the magnetic anomalies and volcanic activity [107] suggests that the Canary Islands may have been generated along a major strike-slip fault zone in continuity with the Transmoroccan fault system.

The presence of abundant alkaline volcanics in the Middle Atlas, combined with the low seismic velocities, points to a thermally anomalous mantle, that likely contributes to regional uplifting [114].

During the Pliocene and Quaternary, horizontal bending and thrusting were accompanied by uplift across the Atlas belt, at rates below 1 mm/y (e.g., [2,115,116]).

3. Nubia–Eurasia Convergence Trend

Any attempt at recognizing the Plio–Quaternary geodynamics of the northern Nubian belts is obviously conditioned by the Nubia–Eurasia kinematics adopted. The analysis described in this work is based on the plate convergence trend (SSW–NNE) that is compatible with the Mediterranean Plio–Quaternary deformation pattern [9,10,71,72]. Given that this trend is significantly different from the one suggested by the kinematic models largely adopted in the literature, it seems opportune to report some remarks about our choice.

The solutions suggesting an SE–NW convergence trend are mainly based on the computation of global kinematic models (GKMs, [117,118]) and on geodetic observations [40,119]. However, the assumptions underlying these computations do not consider some major problems, as discussed by [8–11,72] and synthetically described here below.

- The computation of GKMs is based on a two-plate mosaic: Nubia and Eurasia. However, this choice does not take into account that there are two microplates (Morocco and Iberia) that may not move in close connection with the major plates. In [72], it is shown that adopting the proposed four-plate mosaic (Nubia, Eurasia, Iberia and Morocco, Figure 4), the Nubia–Eurasia convergence trend compatible with the Mediterranean deformation pattern (SSW–NNE) can match within errors the constraints used for the computation of the GKM (Atlantic spreading rates and transform fault azimuths).

- The use of geodetic data in some structures that are moving independently from Nubia and Eurasia may be misleading. This holds for the Iberia and Morocco blocks, the Hyblean–Pelagian domain and the Atlas–Tell system, for the reasons described earlier.
- Geophysical and geodetic data indicate that the Adria domain is now moving roughly north–northeastward with respect to Eurasia (e.g., [120–123]). Since no significant decoupling is actually recognized between Adria and Nubia (e.g., [7,9,10,40,100,124,125]), one should explain how the motion of Adria can be reconciled with the presumed almost perpendicular northwestward motion of Nubia.
- The Nubia–Eurasia rotation poles obtained by the use of long-term geological data [117,118] are significantly different from the ones based on geodetic data [40,119]. So far, the fact that the “geological” poles are located 3000 km north of the “geodetic” poles has not found plausible explanations [118]. This problem may be related to the fact that the kinematic field derived from geodetic data can be considerably influenced by the post-seismic relaxation triggered by strong earthquakes in the last decades. In particular, one can reasonably expect that the kinematic field in the Mediterranean regions is still conditioned by the effects of the major seismic sequence that has developed along the North Anatolian fault since 1939 [9,42,43,126].
- The tectonic implications of the NW–SE Nubia–Eurasia convergence trend cannot be reconciled with several major tectonic features of the Mediterranean Plio–Quaternary evolution, which rather implies an SSW–NNE trend [9,10,71,72].

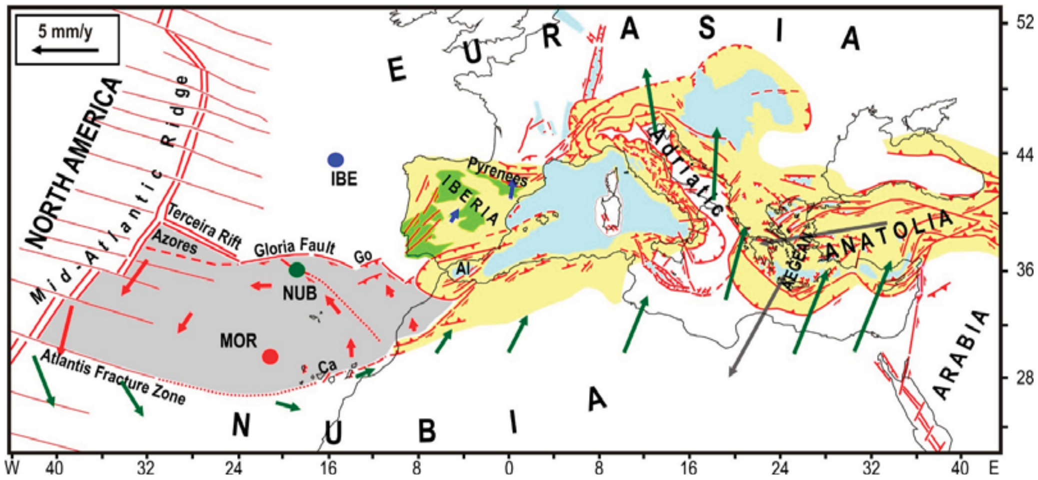


Figure 4. Plate configuration and Pleistocene kinematic pattern in the Mediterranean region, with respect to Eurasia [10,72]. IBE, MOR and NUB indicate the Euler rotation poles of the Iberian (green), Moroccan (gray) and Nubian plates with respect to Eurasia. Blue, red and dark green arrows indicate the plate motions predicted by the IBE, MOR and NUB poles, respectively. The gray arrows in the Anatolian–Aegean system are inferred from geological evidence. Al = Alboran wedge, Ca = Canary Islands, Go = Gorringe bank.

4. Seismotectonics of the Western Mediterranean Region

Seismic activity in this area mainly occurs in the Tell, Rif and Betics belts (e.g., [21,127]) and along the Transmoroccan transpressional fault zone (Figure 5, [20,22,23,128,129]). The fact that most major earthquakes in the northern Nubia margin occurred in these belts (Figure 5) cannot surprise, since such structures were built up by the accumulation of cold and rigid upper crustal material. One can also note that several shocks are located around the Lesser and Greater Kabylides. This may indicate that seismic activity is mainly controlled by the compressional interaction of those metamorphic units with the Tell structures. Significant seismicity is also generated by the thrust faults recognized in the Kabylides offshore, where the Neogene oceanic crust underthrusts the Algerian margin [16,19,27,32].

In the Tell, the analysis of seismicity and neotectonic data indicates SE–NW compression and dextral shear (e.g., [21,37,38]). This strain regime is compatible with the combined effect of the two driving forces proposed here, i.e., the westward push of the Pelagian domain and the north–northeastward push of Nubia.

In the Rif and Betics units, seismicity mainly occurs at the transpressional faults that allow the Alboran wedge (stressed by the convergence between Nubia and Iberia) to escape westward, overriding the Atlantic domain. A major transpressional fault is constituted by the Transmoroccan one, whose seismic activations allow western Nubia to decouple from the Moroccan microplate [9,10,71,72].

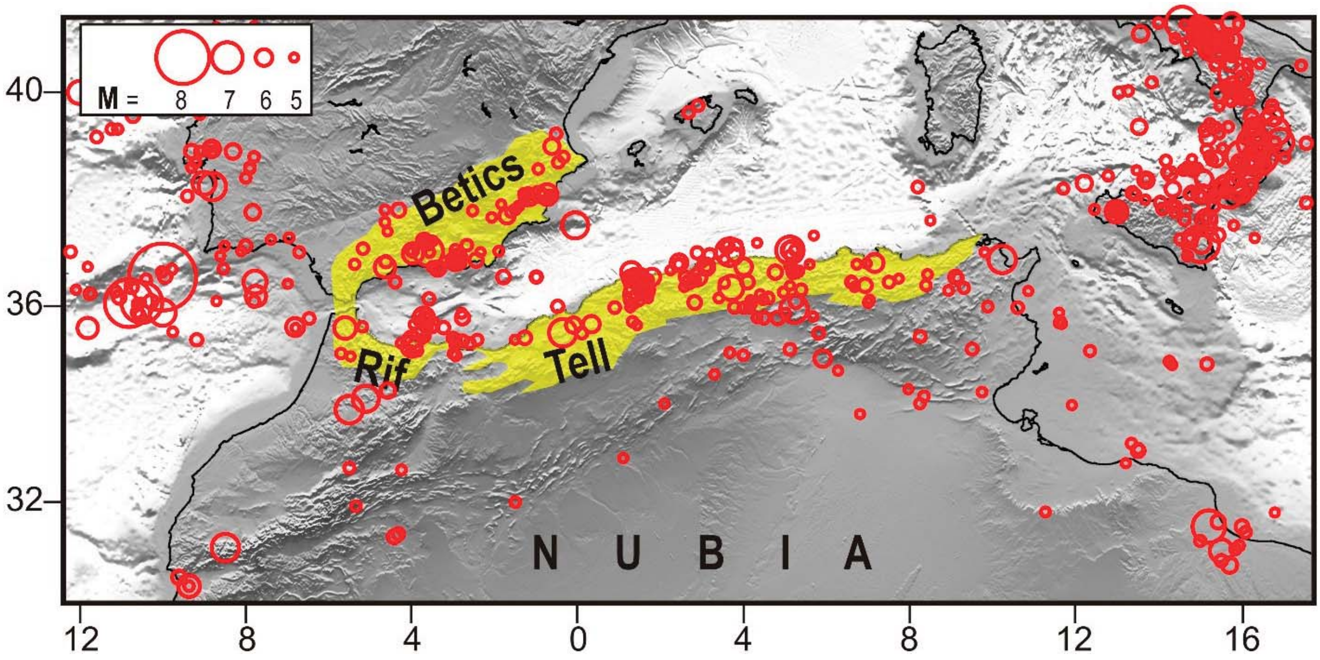
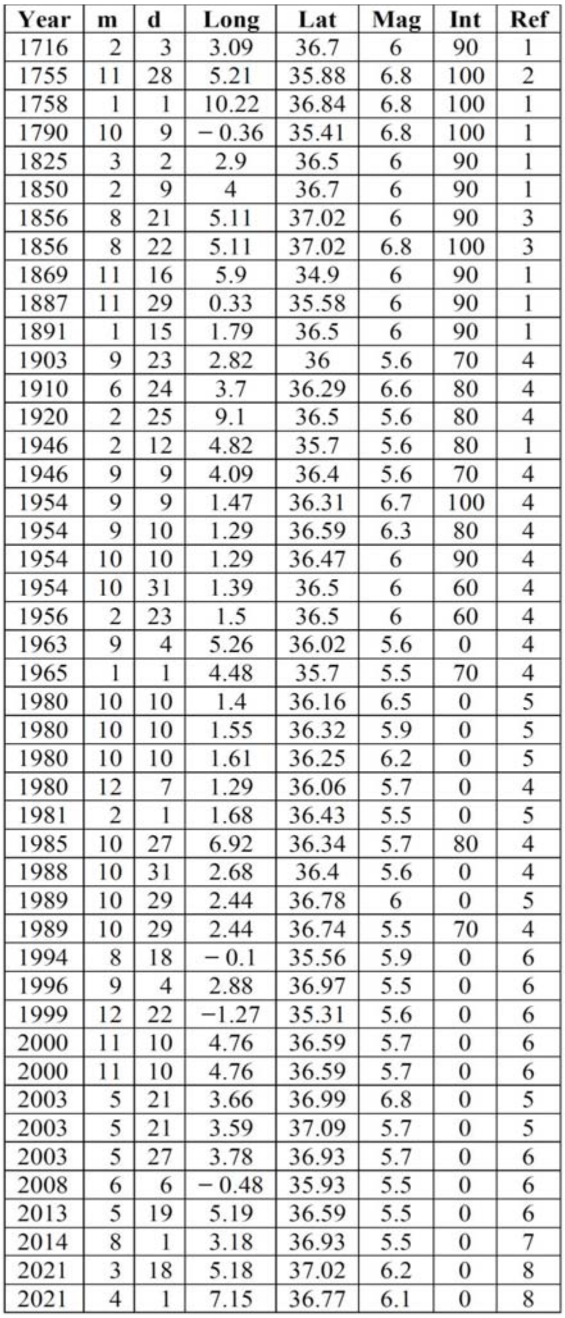


Figure 5. Distribution of major earthquakes (1600–2024) in the study area. Data from [130–141] and Researcher Institutions for Seismology (IRIS), available at https://ds.iris.edu/ieb/ accessed on 1 September 2024.

The geodynamic interpretation proposed here implies that the seismic activity in the Tell system may be influenced by the accelerations of Anatolia. As is known, the development of deformation after major earthquakes is due to post-seismic relaxation, with propagation rates controlled by the rheological properties of the structures involved (Aegean, Adriatic and Hyblean–Pelagian domains, in this case). Insights into the possible development of the above phenomenon in the Anatolian–Aegean system since 1939 can be derived from the tentative modeling of this phenomenon [42,43], even though the conditions assumed in that modeling are very simplified and only related to the initial 1939 Erzincan, Eastern Turkey seismic event. Thus, the results obtained by that investigation can be considered an underestimate of the real effects. To try a recognition of the effects of the above phenomenon based more on observed features, we have considered the time pattern of seismic activity in the Tell system (Figure 6). It is worth noting that the number of major earthquakes in that zone considerably increased in the last decades. For instance, one can consider that 27 events with a magnitude M $\geq$ 5.5 have occurred in the Tell since

1954, while only 9 events occurred in the previous, much longer time interval (1600–1953). It is known that the increase in seismicity rates over time may be partially due to the incompleteness of seismic catalogues for the older periods. However, this can hardly justify the marked difference mentioned above. Considering the timing of the Anatolian seismic sequence (started in 1939) and the results of post-seismic relaxation modeling, one should take into account the possibility that the above increase in seismic activity in the Tell was significantly influenced by what happened in the eastern–central Mediterranean region since 1939 (e.g., [142]).



Year	m	d	Long	Lat	Mag	Int	Ref
1716	2	3	3.09	36.7	6	90	1
1755	11	28	5.21	35.88	6.8	100	2
1758	1	1	10.22	36.84	6.8	100	1
1790	10	9	− 0.36	35.41	6.8	100	1
1825	3	2	2.9	36.5	6	90	1
1850	2	9	4	36.7	6	90	1
1856	8	21	5.11	37.02	6	90	3
1856	8	22	5.11	37.02	6.8	100	3
1869	11	16	5.9	34.9	6	90	1
1887	11	29	0.33	35.58	6	90	1
1891	1	15	1.79	36.5	6	90	1
1903	9	23	2.82	36	5.6	70	4
1910	6	24	3.7	36.29	6.6	80	4
1920	2	25	9.1	36.5	5.6	80	4
1946	2	12	4.82	35.7	5.6	80	1
1946	9	9	4.09	36.4	5.6	70	4
1954	9	9	1.47	36.31	6.7	100	4
1954	9	10	1.29	36.59	6.3	80	4
1954	10	10	1.29	36.47	6	90	4
1954	10	31	1.39	36.5	6	60	4
1956	2	23	1.5	36.5	6	60	4
1963	9	4	5.26	36.02	5.6	0	4
1965	1	1	4.48	35.7	5.5	70	4
1980	10	10	1.4	36.16	6.5	0	5
1980	10	10	1.55	36.32	5.9	0	5
1980	10	10	1.61	36.25	6.2	0	5
1980	12	7	1.29	36.06	5.7	0	4
1981	2	1	1.68	36.43	5.5	0	5
1985	10	27	6.92	36.34	5.7	80	4
1988	10	31	2.68	36.4	5.6	0	4
1989	10	29	2.44	36.78	6	0	5
1989	10	29	2.44	36.74	5.5	70	4
1994	8	18	− 0.1	35.56	5.9	0	6
1996	9	4	2.88	36.97	5.5	0	6
1999	12	22	−1.27	35.31	5.6	0	6
2000	11	10	4.76	36.59	5.7	0	6
2000	11	10	4.76	36.59	5.7	0	6
2003	5	21	3.66	36.99	6.8	0	5
2003	5	21	3.59	37.09	5.7	0	5
2003	5	27	3.78	36.93	5.7	0	6
2008	6	6	− 0.48	35.93	5.5	0	6
2013	5	19	5.19	36.59	5.5	0	6
2014	8	1	3.18	36.93	5.5	0	7
2021	3	18	5.18	37.02	6.2	0	8
2021	4	1	7.15	36.77	6.1	0	8

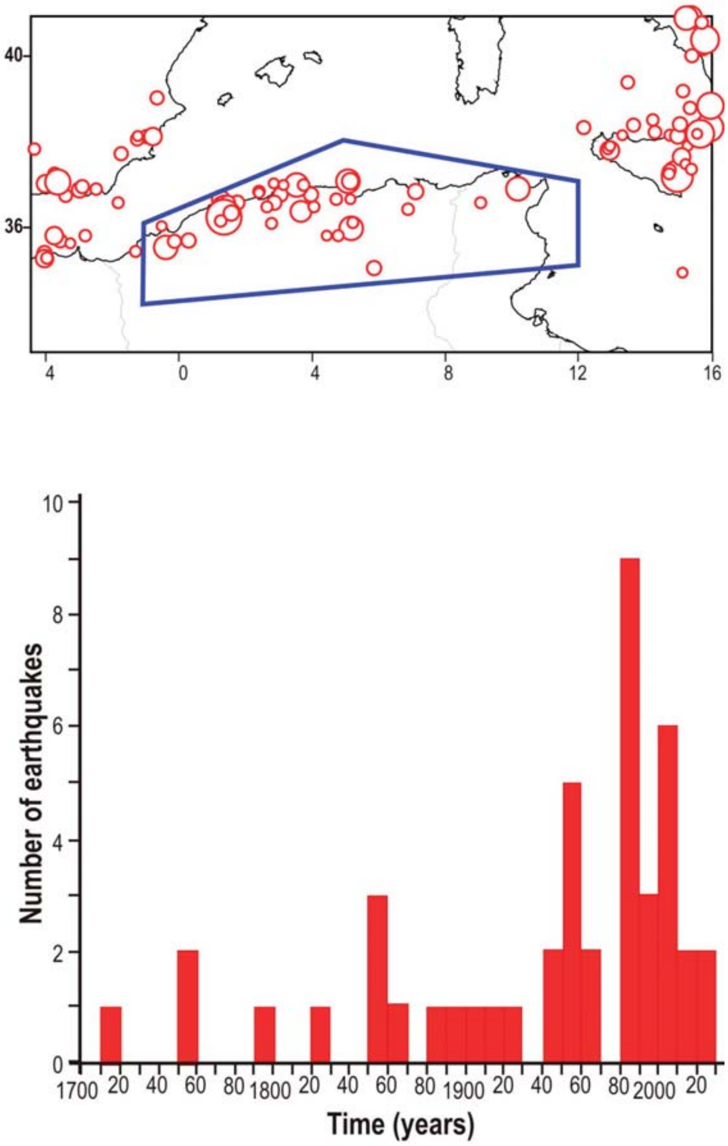


Figure 6. Table of the main earthquakes (magnitude M ≥ 5.5) that occurred since 1700 in the Nubian zone shown in the map (blue polygon). The number in the last column indicates the respective reference: (1) [134], (2) [143], (3) [131], (4) [133], (5) Researcher Institutions for Seismology (IRIS), available at https://ds.iris.edu/ieb/ accessed on 1 September 2024, (6) [137], (7) [135], and (8) [140]. The histogram shows the time pattern of the number of earthquakes with M ≥ 5.5 in the decades since 1700.

5. Discussion

The spreading of opinions about the Plio–Quaternary geodynamics of the northern Nubian belts is mainly conditioned by two assumptions commonly adopted in investigating this problem. The first is based on the idea that the deformation pattern in the central and western regions has not been influenced by the westward escape of the Anatolian wedge. This belief is largely supported by the kinematic field inferred from space geodetic data, which indicates a much faster motion of the Aegean zone with respect to Anatolia, and by the speculative hypothesis that this pattern also relates to the Plio–Quaternary evolution. However, this view overlooks the possibility that such a pattern can represent a transient stage of the post-seismic relaxation that was triggered by the major activation of the NAF since 1939.

The second main assumption postulates that in the Plio–Quaternary evolution, the Nubia–Eurasia convergence trend was oriented SE–NW. This trend, however, is inconsistent with the major tectonic features across the whole Mediterranean area. In particular, with the north–northeastward motion of the Adriatic plate and the configuration of the Hellenic arc (e.g., [9,72]). Furthermore, the methodology underpinning this kinematic interpretation relies on an oversimplified plate mosaic. The SE–NW Nubia–Eurasia convergence trend is also derived from the interpretation of geodetic data in some central (Hyblean–Pelagian domain) and western Mediterranean zones (northern Nubia). However, this interpretation may be misleading if these zones do not move in close connection with Nubia (Figures 1 and 3c). Tentative support for the SE–NW Nubia–Eurasia convergence is also based on the orientation of stress indicators in Iberia and the Alboran wedge (e.g., [144]). Nevertheless, this evidence could be compatible with the SSW–NNE convergence, when considering the complex kinematics of the various structures involved in the western Nubia–Alboran–Iberia–North Atlantic–Eurasia collision zone (e.g., [72]). An example of evidence that can provide important insights into the motion trend of Nubia is the orientation of the Transmoroccan fault system. Since this discontinuity was generated to allow western Nubia to decouple from its northwestern edge (Morocco), it is very difficult to reconcile the trend of that fault with an almost perpendicular motion of Nubia.

Thus, it becomes clear that starting from the above speculative assumptions, many attempts to identify the driving force of the Pleistocene tectonic activity in the northern Nubia margin have finally proposed the Nubia–Eurasia convergence as the main factor responsible, even though this choice must face major problems. For instance, it is not easy to explain why tectonic activity in the Nubian belts reactivated after a period of reduced deformation. To explain this peculiar evolution one should presume a very unlikely discontinuous motion of Nubia.

A critical feature that may impose significant constraints on the geodynamics of the northern Nubia margin, is the transpressional regime recognized in the Tell. This stress field is difficult to interpret solely as a result of a simple plate convergence. Explaining such a strain pattern as an effect of the two driving forces proposed here, i.e., the SSW–NNE Nubia–Eurasia convergence and the westward motion of the Adriatic–Pelagian domain, is much easier. This dynamic solution also provides a coherent framework for understanding the very complex Plio–Quaternary deformation pattern in the central and western Mediterranean regions (e.g., [72]). Moreover, the hypothesis that seismotectonic activity in the Tell can be influenced by the extrusion of Anatolia could explain why seismic activity in that zone has undergone a marked increase in the past decades, just when one can expect the most important effects of the post-1939 westward jump of Anatolia.

Tectonic activity in the Moroccan zone has been mainly driven by the collision of western Nubia with the Alboran wedge and the Iberian block. Major earthquakes along the Transmoroccan fault system have enabled the decoupling of the Moroccan plate from the Nubian plate [10,71].

6. Conclusions

The Plio–Quaternary tectonic activity in the northern Nubian belts can plausibly and coherently be explained as an effect of the westward displacement of the Adriatic–Pelagian domain, driven by the Anatolian–Aegean Tethyan system. This interpretation also account for the complex spatial and temporal distribution of the Plio–Quaternary tectonic processes in the central Mediterranean region. A reliable reconstruction of the present tectonic setting can help to understand the short-term development of the processes controlled by post-seismic relaxation. As an example of this approach, some considerations are reported about the possible connection between the major activation of the north Anatolian fault since 1939 and the significant increase in seismic activity that the Tell zone has experienced in the following decades.

Author Contributions: Conceptualization and methodology: E.M. and M.V.; Investigation and data curation E.M., M.V., D.B., C.T.; Writing E.M.; Fund acquisition: E.M. and M.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Regione Toscana (Italy), Department of Seismic Prevention, grant number: B65F19003190002.

Data Availability Statement: This information was reported by the cited references.

Conflicts of Interest: The authors declare no conflict of interest.

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